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PREPARATION OF MIRRORS FOR ASTRONOMICAL TELESCOPES

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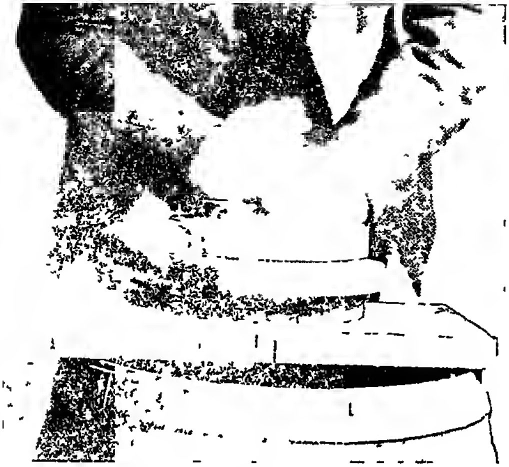

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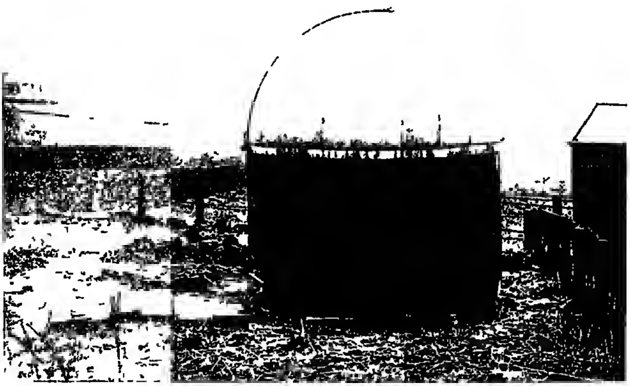

An amateur's observatory

PREPARATION OF MIRRORS
FOR
ASTRONOMICAL TELESCOPES

BY

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BLACKIE & SON LIMITED
LONDON AND GLASGOW

Printed in Great Britain by Blackie & Son, Ltd, Glasgow

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PREPARATION OF MIRRORS FOR ASTRONOMICAL TELESCOPES

CHAPTER I

Introduction

Pioneers.

Amateur astronomers, as well as professionals, as they behold the beauties of the sky unfolded to their gaze through a telescope, cannot fail to recognize the genius of that band of early workers, who, with so much anxious thought and perseverance, have made such an instrument of delicate precision possible.

Nearly 270 years have elapsed since Newton first applied his genius to perfecting the reflecting telescope, a lead which was followed by men of such outstanding ability as Herschel, Rosse, With, Common and others Foucault and Liebig both made substantial contributions to the perfection of the present-day reflector, the former with a means of rendering its delicate curve more visible to the eye, and the latter with a means of depositing a fine coat of highly polished silver on its surface.

Newton's Telescope.

Newton, with his own hands, made a small reflector which is now preserved in the collection of the Royal Society as one of its greatest treasures With this telescope, which has

an aperture of only $1\frac{1}{3}$ in. and a length of $6\frac{1}{4}$ in , Newton was able to view the phases of Venus and Jupiter's satellites. This tiny telescope was destined to be the forerunner of the world's largest telescopes of the type which now bear his name.

Herschel.

Perhaps the greatest master of the reflector was Sir William Herschel He presented the astronomical world of his time with telescopes of larger size than any which had ever been seen before, including one of 4 ft. diameter, a truly wonderful achievement in view of the meagre facilities available at that time Had the knife-edge test been available to Herschel and With in their work, there is no saying to what extent the world of science would have benefited by their skill. Considering that those workers had to work more or less in the dark, the standard of perfection reached by them was very high.

The present-day amateur in his work has the benefit of all the experience of those early workers, who began as amateurs and finished as professionals of the highest rank. Some of our present-day leading experts began work as humble amateurs and have reached their present position through perseverance and a keen interest in the art of telescope making

Speculum Metal.

Up till about the middle of the nineteenth century, astronomical mirrors, or specula, were made of speculum metal, a 68/32 mixture of copper and tin which is exceedingly hard and has the property of taking a very high polish. Newton and Herschel had of necessity to make their specula of speculum metal, as the process of depositing silver on glass was not then known The reflective power of speculum metal, compared with silver on glass, is very poor, although to the eye the former may look the brighter of the two.

Principle of Newtonian Telescope.

As its name implies, the action of the reflector depends on the reflection of the light collected by the mirror. Reference to fig. 1 will enable the principle of Newton's reflector to be easily understood.

The parallel rays of light coming from a distant object are collected by the concave mirror A. On being reflected they would come to a focus at the point B, but a small flat mirror is interposed at C, which deflects the rays of light through the side of the telescope tube to the point D, where they can be examined by a magnifying eyepiece In this position the head of the observer is clear of the main rays of light entering the telescope tube, which would not be the case if the eyepiece was applied at B

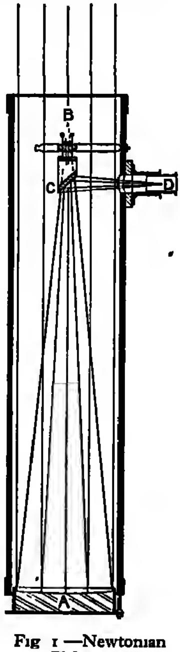


Fig 1 —Newtonian Telescope

The " flat ", or " diagonal ", C, must be as small as possible in order to avoid loss of light, as the flat is directly in the path of the rays entering the telescope For the same reason the flat is usually made of oval shape, so that when it is set at an angle of 45° to the axis of the telescope it will present a round section to the rays of light passing down the tube This may be better understood if a broom handle is cut at 45° and a small piece cut off to represent the flat.

Further, to avoid loss of light, the arrangement for supporting the flat is usually a single arm of flat section presenting the narrow edge to the path of the rays, or else a " spider ", consisting of three equally spaced arms of thin metal strip with tensioning screws at the ends, so arranged that they present an edge on view in the axis of the tube

CHAPTER II

Glass and Polishing Materials

Survey.

Newton and later workers fully realized the drawbacks of speculum metal as a material for the reflectors of their telescopes. Every time a speculum became tarnished and required repolishing, it meant disturbing the curve on which they had expended so much care and patience. When the process of chemically depositing a fine film of pure silver on glass was discovered, speculum makers saw that here was the ideal for which they had been waiting. By making their reflector of glass and coating the surface with silver it was a simple matter when the silver became tarnished to dissolve it off and resilver without disturbing that precious curve. As the result of this discovery astronomical mirrors are now almost exclusively made of glass, even in the largest sizes. The 100-in. Mount Wilson, the largest reflector in the world, is made from pyrex glass, and was until a few months ago silvered in exactly the same way as the modest 6- or 8-in. instrument used by the amateur. Recently a new process was discovered called " aluminizing ", whereby a thin coating of aluminium is deposited under vacuum, and gives a practically untarnishable surface and superior reflective power. The great boon of this new process in the case of the 100-in. Mount Wilson telescope (which is now aluminized) can be realized when the saving in labour of dismantling and cost of silvering every six months is considered against aluminizing every few years.

Glass.

A few minutes' study of the properties of glass and its behaviour under change of temperature will greatly aid the fuller understanding of the succeeding chapters. Common

glass is produced by the fusion of a mixture of sand and carbonates of lime and soda at temperatures of from 1200° C. to 1500° C Crown, flint and special glasses are simply the result of varying the constituents of the mixture. For astronomical mirrors the colour of the glass does not in the least matter, provided it is capable of taking a high polish, the glass being only a base for the reflecting film of silver, whereas the expensive crown and flint glasses used in the object glass of a refracting telescope pass all the light through

Effect of Temperature.

Glass is well known to be a bad conductor of heat, and it is this characteristic which set the early worker so many problems, only understood and mastered by sheer tenacity of purpose and patience When a piece of thick glass is subjected to a sudden rise of temperature, say 5° or 10°, the outside surface expands first, leaving the interior behind In this condition strains are set up, powerful enough to distort the glass from its normal shape; consequently if the change in temperature is a very violent one, such as may be produced by immersion in boiling water, the glass will fracture or crack It is *changing* temperature which causes the trouble, if the change takes place more rapidly than the glass can respond The effect of this will be very apparent at a later stage during polishing and testing.

Pyrex.

Pyrex glass, which has come into so extensive use in recent years for cooking utensils, has a better conducting capacity than plate-glass and is much superior as a medium for mirrors. Changes of temperature affect it in exactly the same manner, but to a much less degree, in fact, for normal atmospheric variations of temperature the change of figure is so small as to be almost negligible Almost all the larger telescopes have their mirrors made from pyrex, including the new 200-in at present under construction, which was

recently cast at the Corning glass works for the Carnegie Institute of Technology in co-operation with the Mount Wilson Observatory, Pasadena The search for the ideal material still goes on. A considerable amount of research and experiment has been carried out in all parts of the world both by the expert and the amateur, resulting in a few minor advances, for example stainless steel and sectional or built up quartz mirrors, but neither of these has so far seriously competed with the orthodox glass.

Fused quartz is definitely superior to anything yet discovered, its coefficient of expansion being about $\frac{1}{20}$ that of common glass, but the technical difficulties experienced in its manufacture in sufficiently large quantities have so far prevented its use for large astronomical telescope mirrors It can be obtained in discs suitable for amateurs' use, but the price may prove to be rather prohibitive.

Carborundum.

Glass, though brittle, is a hard substance Something harder, therefore, must be used to grind or work it. Up till the end of last century emery was the hardest known substance available as an abrasive (excepting diamonds, which were obviously too expensive) In 1898 chemists at the Niagara Falls electric works, with unlimited supplies of electrical energy at their disposal, in attempting to separate out pure silicon from siliceous sands by fusion, formed a new substance, carbide of silicon, which proved to be extremely hard, much harder than emery. The commercial possibilities of this were soon realized, and by 1900 it became available as an abrasive under the name of carborundum. Compared with emery, carborundum cuts about six times as fast It is obtainable nowadays in a variety of grades. For hand grinding operations the grades commonly used are Nos 60 or 80, 220, 3F, 400 and 600 The price is moderate—*1s* *6d.* a pound for the coarser grades to *2s* a pound for the finest. The Carborundum Co., Trafford Park, Manchester,

will willingly supply direct It is sound policy to deal direct with the makers, as then there is less risk of the finer grades being contaminated with stray grains of coarser abrasive, which would prove fatal to fine grinding

Rouge.

Fine as No 600 carborundum is, it will not polish glass, though a good fine ground surface should show a semi-polished lustre. In polishing glass for optical work, rouge (red oxide of iron) is almost universally used Good quality optical rouge is fairly easily obtainable, but some kinds are liable to scratch in use and need preliminary treatment by settling out in water B quality optical rouge, supplied by Canning & Co , Great Hampton Street, Birmingham, is reliable and can be used without preliminary treatment. The price is 1*s*. 6*d* per ½-lb tin, sufficient to polish quite a few mirrors

Pitch.

Commercially, felt is used as a carrier for the rouge, but for the highly polished and accurate surfaces of astronomical mirrors pitch is recognized as the best medium. Pitch, a by-product of coal tar distillation, is a peculiar substance, flexible yet brittle It will flow if given enough time, as can be proved by leaving a lump in a box for a week or so, at the end of which it will be found to have flowed in an even layer across the bottom, yet a sharp tap will shatter it into fragments. It will yield to gentle pressure, but sudden bending will break it. It is this characteristic of being hard yet plastic which makes it an ideal base for the accurate polishing of glass. English, Russian or Swedish pitch is stocked by most dry-salter's stores, and the price is about 10*d* per lb. From such a source it can generally be relied on to be clear and free from grit and foreign matter As a cement for fixing handles to glass, pitch is ideal, a sharp sideways tap being all that is needed for safe detachment Pitch may be tempered or

made hard or soft at will Prolonged heating will harden it By the addition of a small percentage of turpentine it can be softened to any required degree Genuine American turpentine should invariably be used, as the substitute turps is a poor solvent of pitch and is useless for cleaning off operations.

A word of warning about the melting of pitch may save trouble and possible danger. When overheated it gives off a dense, strong-smelling vapour which is highly inflammable. Should this accidentally catch fire, extinguish by smothering or covering with a lid or even a piece of card. For the same reason care is necessary when adding turpentine.

CHAPTER III

Tools and Materials

Glass Discs.

The beginner will be well advised not to be too ambitious and aim too high A 6-in. mirror is quite large enough to start off with When it is considered that an 8-in. mirror contains roughly twice the area of glass of a 6-in, it is apparent that the difficulties of working are increased out of all proportion to the diameter A higher degree of skill is therefore necessary if success is to be expected with a mirror over 6 in

For a first attempt plate-glass is quite good enough. A 6-in mirror of commercial plate figured to the limit of the beginner's skill will give quite a good account of itself on the moon with medium powers up to 100, and will be a stepping stone of encouragement to something better. Only on higher powers 250 to 300 will the user discover the defects

of inferior workmanship, and only then will temperature changes make themselves apparent

On larger sizes pyrex will certainly show its superiority under changing temperature conditions, but plate-glass is not to be despised, as some quite good instruments of fairly large size have been made by well-known amateurs. The limit for the average individual to master by hand methods is about 12 in., although larger sizes have been successfully made and used by experienced hands.

Flexure.

Any reliable glass company will supply plate-glass rough cut into circles of any size and thickness It may be difficult at first to appreciate that if not thick enough, glass will bend or sag, under its own weight or during working, sufficiently to upset the curve of a really good mirror To overcome this a thickness of not less than one-sixth of the diameter is required, so that for a 6-in. size a disc cut from 1 in standard plate will be suitable A second disc of the same diameter is required as a tool to grind the mirror on, but it need not be as thick as the disc for the mirror About one-ninth the diameter will be sufficient, say a disc cut from ¾ in. plate. Two such discs 6 in diameter cost from 7*s* to 9*s*, the price varying according to the suppliers' facilities for cutting.

Pyrex may be obtained direct from the makers, James A Jobling & Co , Ware Glass Works, Sunderland, and costs about twice as much as plate-glass It is usually supplied rough ground to size and can be had ready edged to size at a slight extra cost As pyrex discs are cast to requirements and not cut from stock sheet, a standard size according to the makers' moulds may have to be selected. In the casting of pyrex tiny air bells or bubbles are very difficult to eliminate, and a disc as received should be carefully examined for air bells near the surface, and the better side selected, as trouble may be experienced during grinding if some of these happen to lie on the surface of the finished curve. This is one reason

why beginners are advised to start with plate-glass; another is that pyrex is harder both to grind and polish A plate-glass tool is quite satisfactory for grinding a pyrex disc, and it is unnecessary extravagance to use any other.

A good quality crown glass is supplied by Chance Brothers, specially for mirrors, and although about twice the price of plate, is recommended by some of the more experienced workers. It can be relied on to be of uniform quality and properly annealed, with a temperature coefficient between that of plate-glass and that of pyrex

The Tool.

For the amateur who only anticipates the making of one mirror at most of any one size and curvature, a glass grinding tool is undoubtedly the cheapest and best In this connexion the word " tool " is used in a special sense, and should not be confused with the word as used in the general sense of a working instrument The " tool " is the mould or former on which the glass disc is ground to the required depth of curve On large-scale repetition work, opticians use brass or cast-iron tools turned and ground true to curve Such tools are essential if a number of mirrors or lenses are to be made of the same curvature or focus, but for the amateur the difficulties of making such tools outweigh their advantages All the giant telescope mirrors, it is true, are ground with special metal tools, but here it is a case of necessity, owing to the enormous weight of the glass, which cannot be handled in the same way as the amateur's small size.

Barrel.

Before work is commenced a few simple accessories should be obtained and prepared

As a work bench during grinding and polishing, an empty barrel is required Any substantial barrel of convenient height may be utilized. The small kegs in which preserved

ginger is sent out are very convenient for this purpose, being small in diameter and thus enabling the worker to get nearer his work One end should preferably be taken out and a 1-in. board 8 in or 10 in broad screwed across the mouth in such a manner that the hand can be inserted to screw on a thumb-screw for attaching the tool (see fig 2 and Plate I).

The purpose of the barrel is to allow the worker to walk round the tool during grinding, this will be better understood when the process of grinding is actually started The corner of a steady table or a bench may be used, but this only allows

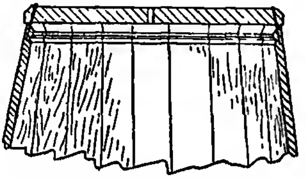


Fig 2 —Section of the top of a barrel showing method of fixing board to top

travelling in half-circles, and is not to be recommended for the beginner, owing to the risk of getting an irregular curve. An experienced worker, however, may succeed in producing quite good results

If some mechanical arrangement can be devised for slowly rotating the tool, say once or twice per minute, the barrel may be dispensed with, and any convenient bench or support used instead.

Fixing Handles.

For handling the glass discs during working, some form of handle, preferably of wood, must be fixed to the back by means of pitch. To do this properly the glass is gently warmed over an oil stove or in an oven till it is just uncomfortable to touch with the back of the hand, and a little turpentine is

smeared on with the tips of the fingers or a tuft of cotton-wool. A small quantity of pitch (which has previously been melting) is poured on the warm glass, then the wood is gently pressed on until the pitch spreads and oozes out all round. It must then be left aside on a level support to cool. By this treatment the glass will be securely attached to the wood and will stand a surprising amount of abuse without becoming disconnected Examination of the pitch through the back of the glass will show at a glance whether there are any areas of defective contact or large air bubbles detrimental to the safety of the glass during subsequent handling. The most likely causes of poor adhesion are that the glass has been too cold, or that the smearing with turpentine has been omitted On the other hand, if the glass is made too hot, the turpentine will evaporate before the pitch can be poured on The action of the turpentine seems to be to soften a thin layer of pitch next the glass and make it more adhesive. Hot pitch readily adheres to wood if it is dry, but an extra precaution may be taken by heating the face of the handle prior to pressing it on

Securely as pitch holds anything to glass, it is nevertheless quite easily detached when required. Stand the glass on edge on a firm wooden support. Then hold a piece of wood, end on, against the handle, strike a sharp blow with a hammer, and the handle will come away, leaving the glass clean and free from pitch Any pitch left adhering to the glass may be scraped off and wiped clean with turpentine and a tuft of cotton-wool or rag

Some workers prefer a fifty-fifty mixture of beeswax and resin as being cleaner to handle than pitch This mixture is not quite so flexible as pitch and had better not be used if there is any risk of the wood back warping during use.

If a turning lathe is available, an assortment of handles may be turned up In selecting a handle for grinding, a good area of contact is advisable, as the force applied is considerable, and sufficient to detach a small handle such as would

do for polishing The handle must be securely fixed in the backplate, or it may come adrift during coarse grinding. Fig 3 will make the method of fixing clear

Quite good handles can be made from the wood bobbins, on which insulated instrument wires are supplied, by cutting off one flange.

At this stage a list of materials will be useful and may save purchasing excessive supplies.

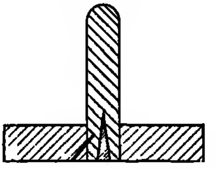


Fig 3 —Method of fixing handle into wooden backplate.

LIST OF MATERIALS

1 lb No. 80 carborundum powder.
½ lb No. 220 " "
2 oz or ¼ lb. each of Nos 320, 400, 500 and 600.
½ lb Oakey's best washed flour emery ⎫ From a drysalter's store.
2 lb Archangel pitch ⎬
½ lb beeswax ⎪
1 gill pure American turpentine ⎭
½ lb. best optical rouge.
1 best polished plate-glass circle 6 in. diameter by 1 in. thick.
1 best polished plate-glass circle 6 in. diameter by ¾ in thick

With the above supply of materials work may now be started in earnest

Edging.

Purchasing the rough cut glass circles and edging them oneself has quite a lot to recommend it For one thing it is cheaper, but by far the most important point is the preliminary experience gained in the use of carborundum and the revelation of its cutting power.

The process of edging is fairly simple and should be done

before grinding and polishing is attempted Some mirrors are ground and polished first and edged afterwards, but the difficulty arises of adequately protecting the optical surface of the finished mirror against scratching by the abrasive. Access to a turning lathe is a big asset, although not absolutely essential. A spindle, with a faceplate or disc on one end fixed up on two bearings with a good strong handle for turning, will be found quite effective though slower and entailing much harder work

Fig 4 shows the principle of edging A is the glass disc B is a band of sheet iron about $\frac{1}{16}$ in thick and about 1 in.

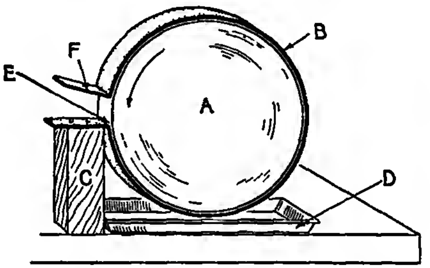


Fig 4—Edging the Glass Discs

wider than the glass C is an anchorage to which the end of the iron band is secured A tin tray D, placed under the disc while edging, serves the double purpose of saving a bad mess and enabling any unfinished carborundum to be collected and reused For those whose mechanical experience is limited the following description should make the process clear. A disc of wood about $\frac{3}{4}$ in thick and 1 in smaller in diameter than the glass is fixed with screws to the faceplate of the lathe or spindle and trued up.

Unscrew the faceplate; cement the wood to the glass with pitch, and while the pitch is still soft, screw the faceplate on again and true up the glass by gentle pressure on the high side until the whole runs true. When it is sufficiently firm to

stay fixed, unscrew the faceplate and set it on a level surface to cool If left on the lathe while the pitch was yet soft, the glass would gradually slide down by its own weight When it has properly set, and not before, reassemble on the lathe with the band Run the lathe in the direction of the arrow at about 80 r p m and feed a mixture of No. 80 carborundum and water into the revolving disc at E, at the same time applying pressure at F After a few minutes the rate of feeding will soon be " sensed " by the sound of the grinding.

As the grinding proceeds the tray underneath will collect quite an amount of ground glass, mixed with unused carborundum Some of the best of this (i e. coarsest) may be scraped up and fed back through, care being taken to keep the glass disc well supplied with water. If it is run too dry the glass will clog and heat up, and there is a risk of the pitch softening and of the whole coming adrift, with unpleasant results

If the glass has been cut near to the required size, ten to fifteen minutes' work should be sufficient for No 80. If at the end of that time the desired size is not reached, carry on with the coarse, checking frequently with calipers. When within $\frac{1}{32}$ in. of the desired diameter change to No. 220. A few minutes of 220 should suffice to give quite a smooth finish There is no necessity to wash up between grades during edging, beyond an extra swill of water before changing over

Both the tool and the mirror must be edged exactly to the same diameter It will generally be found that the mirror disc will clean up to a smaller diameter than the tool owing to the rougher edge left in cutting the thicker glass, so it is advisable to edge it first and bring the tool down to suit.

Bevelling Corners.

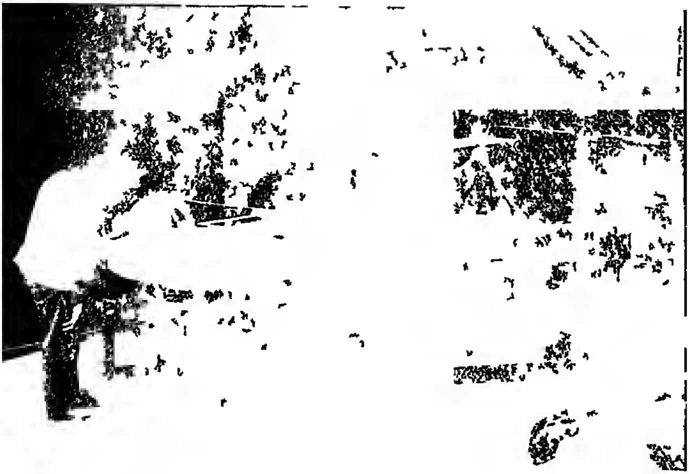
When the discs have been successfully edged, one small but very important operation still remains to be done before proceeding to rough grinding, i.e. bevelling the corners.

The brittle character of glass gives it a tendency to chip at the edges To avoid this the sharp corners should be bevelled or rounded off by honing with a medium carborundum stone and plenty of water. Care must be exercised when starting not to chip the edges with the hard stone by a slight jar. A bevel of $\frac{1}{16}$ in. is sufficient to prevent chipping under ordinary treatment. During rough grinding sufficient glass may be ground away to necessitate renewal of the bevel A careful look-out must be kept against slight accidental knocks, which may result in unsightly chips and so spoil the appearance of otherwise good work A bevel may be ground before the discs are removed from the faceplate by holding a piece of flat iron fed with No 220 carborundum and water at an angle of 45° against the corner while revolving. If this method is adopted it is important that the glass revolves absolutely true with no side wobble, or bad chipping may result In any case, for a satisfactory job, no side wobble should be tolerated when trueing up, or trouble will be experienced later when mounting the mirror in the cell.

Professionally made mirrors of large size are too heavy and unwieldy to be edged by the above simple method, so they are ground much in the same way as engineers grind metal with power-driven carborundum wheels The huge slab of glass is mounted on a slowly revolving horizontal turntable, while an electrically driven carborundum cup wheel is fed against the edge and well supplied with water.

The top illustration on Plate II shows a 42-in. disc during the process of edging in the works of Sir Howard Grubb, Parsons & Co , Ltd , Newcastle-on-Tyne.

Any amateur with the necessary grinding plant and practical skill may obtain very successful results, provided care is taken not to attempt grinding at too high speeds.



1.

Rough grinding .. c c

CHAPTER IV

Grinding

Preparation.

With two glass discs edged to size and with the corners safely bevelled off, the work of rough grinding may now be tackled with confidence. Fix a good substantial handle to the mirror disc with pitch as near the centre as possible.

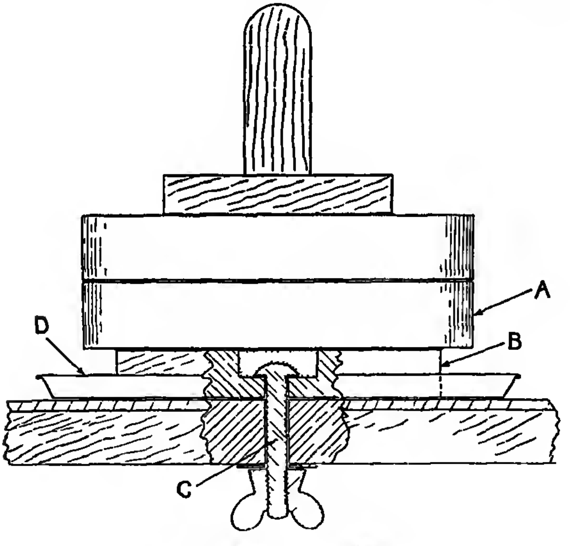


Fig 5 —Tool and Mirror Assembly

If the handle is far off the centre, an irregular curve is likely to result, with added trouble during fine grinding later on. The glass disc for the tool may now be fixed to its wooden back, which should have some means of attaching to the barrel Fig 5 will make this clear

A is the tool, and B is the wood back with a recess for the head of a $\frac{3}{8}$-in bolt C of the required length for taking a thumb nut An important item is a tray D, with a hole in the centre to clear the bolt An old toffee tray is quite suitable, and its benefits will be appreciated when it comes to washing up between grades By keeping the wood back smaller than the tool, the mixture of waste ground glass and carborundum will drop clear into the tray Alternative methods of fixing will no doubt suggest themselves according to the materials available

The barrel must be well weighted with any heavy material available, such as bricks, stones or iron scrap *It must be steady*, with no rock whatsoever If need be, screw it to the floor The necessity for this will be forcibly brought home during grinding, when the mirror begins to drag

Principle of Grinding.

The principle of grinding will be best understood by studying the following sequence of three motions required to produce a truly symmetrical curve First, a back and

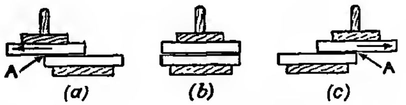


Fig 6 —Positions of Mirror at beginning and end of a stroke

forward motion of the mirror across the tool called the stroke, second, turning the mirror round slightly between each stroke, and third, walking slowly round the barrel once during every 20 or 30 strokes This sequence of motions is much easier to carry out in practice than might appear.

In fig 6*a* the mirror is seen at the end of the forward stroke The backward stroke overlaps to the same amount. In this position the mirror is overhanging the tool by half its diameter. From this it will be seen that the weight of

the overhanging glass is exerting maximum pressure at A, and so will grind faster in the centre of the mirror than at the edges, and vice versa in the tool Consequently it follows that the top glass (or mirror in this case) will grind hollow or concave and the tool or bottom glass will grind convex This is always the case with two pieces of glass and nothing will alter it, the top becoming concave and the bottom convex. With cast iron or similar tools shaped to curve, this tendency is almost non-existent, so that large mirrors can be ground with the tool on top, the weight of glass in the mirror making any other method impracticable

Grinding with straight to and fro strokes only, without turning the mirror or walking round the barrel, would result in two cylindrical curves instead of spherical curves, hence the importance of combining the three motions Some workers use two motions instead of three by omitting to turn the mirror at the end of each stroke The writer's experience is that this is more difficult in practice than the three-stroke method, as some sort of mark has to be made on each glass and kept coincident throughout The speed of turning the mirror at the end of each stroke is not very important About one-eighth of a turn per stroke is quite sufficient, but individual workers after a short spell of grinding will soon find the particular speed suited to their hand The important point is to carry out all the motions

Mechanical Grinding.

All the above movements can, of course, be reproduced by mechanical means, and the mechanically minded could no doubt rig up suitable gear to do the grinding efficiently, but a certain amount of experience is necessary to design a machine to complete the polishing of an astronomical mirror of first-rate quality with a true curve A machine to perform the necessary motions for grinding is of comparatively simple construction (see Plate II) Essentially it consists of a means of rotating the tool, such as a simple belt drive equivalent to

walking round the barrel, and two adjustable throw cranks with rods set at right angles to each other, connecting at and to the centre of the mirror to give the stroke or back and forward motion A means of rotating the mirror may be added by a ratchet device or bevel gearing

Easy adjustment of the length of stroke is necessary, as well as variation of the rotating speeds to counteract any tendency to form zones, which may develop through the too regular repetition of the cycle of operations

Even with a machine of good design a certain amount of experience is required to get good results In any case the figuring or parabolizing cannot be completed by machinery alone, without a certain amount of skilled hand work in the operation So the beginner is well advised to discountenance machinery for the first attempt and to gain experience with hand manipulation and thus be better equipped to take full advantage of mechanical aid

Hollowing Out.

After ten minutes' grinding with No 60 or 80 carborundum and water, an examination will reveal the concave surface developing in the mirror, as may be tested by placing a straight edge or rule across the face

At this point the finished focus of the mirror will have to be decided in order that the hollowing out of the glass may be stopped in time.

As previously stated, the usual ratio of focus to diameter is 8 to 1 or F8, therefore a 6-in mirror will have a focus of 48 in By the laws of optics the radius of a curve of given focus is twice the focal distance, or in this case twice 48 in. = 96 in The actual focal length is not a critical value, and depends on the maker's requirements and ideas on the matter. It may be anything within reason and still perform well, and is only limited by the constructional difficulties of mounting and eyepieces The chief drawback to extremely long focus lies in too long a tube with additional difficulty in reaching

the eyepiece during observation near the zenith. The chief objection to very short focus lies in the fact that the cone of rays is too wide for standard eyepieces, so that special eyepieces will need to be made if full advantage is to be taken of the light-gathering power.

The speed of hollowing out is governed by the length of stroke. The longer the stroke the faster the hollow develops, though the curve may not be a regular part of a sphere, but at this stage it is the quick removal of the glass from the centre of the mirror, rather than regular curve, which is of the greater importance. The curve will come all right during fine grinding with a shorter stroke.

The carborundum may be applied either by sprinkling a fine layer of dry powder over the tool and adding sufficient water to wet thoroughly, or it may be mixed in a jar with water, and a small quantity of powder and water applied with a spoon. With the finer grades the latter method is advisable.

Each application of powder should be worked well out before applying more, but if speed in hollowing out is wanted, and a little extra extravagance in carborundum can be afforded, the worker may apply a fresh dose just as soon as he feels the cutting power is diminishing. When coming near the desired depth of curve, some of the worked-out powder may be scraped up from the tray and reused, this tending towards a smoother surface besides being beneficial to the next stage of fine grinding.

Testing for Curvature.

After twenty minutes to half an hour's grinding, a check of the depth of curve should be made. This may be done in various ways. The simplest and perhaps the best is by means of the spherometer, a small instrument used by the optical trade for measuring spherical curves. It consists of a triangular frame with three hardened points at the vertices and a micrometer screw in the centre suitably graduated for

reading The purchase of one is hardly worth while unless a large number of mirrors is contemplated

Failing a spherometer, one of two other quite effective methods may be used The rough surface left by No 80 is itself non-reflective, but it can be made reflective by dipping in a basin of clean water and draining the surplus quickly. This leaves quite a good reflective surface, which stays on long enough to make a test Set the mirror, while wet, up on edge on a V-block or similar arrangement to prevent rolling, and take a light (a flash-lamp is excellent) and hold it level with the eyes, but to one side, and move it about opposite the face of the wet mirror at a distance estimated equal to the radius of curvature, until the reflection of the light is seen Now observe while holding the head steady the direction in which the reflection travels when the light is moved If the reflected image travels in the same direction as the moving light, the eye is nearer the mirror or within the centre of curvature, and if it travels in the opposite direction the eye is beyond By moving nearer or farther away from the mirror, as the case may be, a point is reached when the light will remain stationary and not travel in either direction, while at the same time the surface will appear full of light The distance from this point is the radius of curvature under test

Another method of finding the *focus* is by sharply focussing the image of the sun or some convenient point and measuring the distance, bearing in mind that it is parallel light which is reflected and therefore the distance measured is the focus of the mirror, not the radius of curvature

Back Treading.

The hollowing out of the curve should not be carried to full depth by coarse grinding, but should be stopped short when the radius is within 10 in of the required distance, e g at 106 in if the final radius is 96 in. The radius will shorten about this amount during the remaining stages of

fine grinding Should it be found on measurement that the curve is too deep, i e radius too short, it may be left at that if so desired, or it can be brought back by simply inverting the tool and mirror and continuing the grinding In this position, if grinding was continued long enough, both tool and mirror would come back to the flat surfaces originally started with On having reached the desired depth of curve, examine the edge to see if the bevel is still satisfactory and renew it if it is much less than the $\frac{1}{16}$ in originally started with. It is unlikely to need further renewal during the subsequent stages of fine grinding.

Washing Up.

Before the next stage of fine grinding can be proceeded with, the mirror, tool and top of barrel must be thoroughly washed It is now that the benefit of the tin tray below the tool will be appreciated Unless the worker has been unduly careless in using the carborundum, there will be no necessity to dismantle the board on top of the barrel, as the tool and the tray will contain all the grit This washing has to be very thorough indeed to get rid of every trace of abrasive Use an old tooth-brush or nail-brush if necessary to get at the crevices and corners Finally rinse well with clean water by holding under a running tap for one or two minutes

As an extra precaution against the possibility of grit remaining, a double sheet of clean newspaper may be placed over the board on top of the barrel, underneath the tray, and renewed after each wash up Any extra precautions taken against stray particles of coarse grit are well worth while, and for the same reason each tin should be kept securely closed up except when actually in use.

Fine Grinding.

When all is thoroughly washed up and reassembled, the tin containing No. 220 may be opened and grinding proceeded with exactly as with No. 80 Long stroke may still

be used for a time if the full allowance of 10 in to 12 in. has been made in the radius of curvature The aim now is more to get a smooth surface than to remove glass, so each application of powder and water should be well worked out before applying more After a few minutes' working the mirror may have a tendency to drag, and the worker is warned against carrying on too far if this happens, or he may find the tool and mirror stuck together so fast that great difficulty will be experienced in getting them apart. A timely application of water will avert this mischance One or two applications of water may be needed before one charge of carborundum is fully worked out

To avoid accident and to prevent the risk of chipping, the mirror should be placed on and off by a sliding motion, not by a direct lift Also never stop moving the mirror for any reason, while it is in contact with the tool, but slide it gently off when necessary

As the surface gets smoother, testing for curvature becomes easier, the water adhering longer and more evenly When the radius of curvature is within about 2 in of the desired length, the stroke should be shortened a little to about $\frac{2}{3}$ to $\frac{1}{2}$ stroke This stroke should be maintained throughout fine grinding except during the last grade when it may be mixed with slightly shorter strokes. Each charge of carborundum will take about five minutes to work out and six charges should be about enough for each grade. Examination with a strong magnifying glass, such as a 1-in Ramsden eyepiece, is useful for showing the condition of the surface. If the outside edge looks fairly regular in texture, with no conspicuous deep pit marks showing from the previous grade, it may be considered satisfactory, and washing up undertaken in preparation for the next grade 3F The same scrupulous care must again be exercised in washing up, not forgetting to change and burn the paper below the tray

The procedure for each successive grade is exactly the same, and if due care is exercised no great difficulty should

arise. Some workers jump from 3F to 600, missing 400 and 500 altogether The writer has tried out going from No. 60 to 220 and then to 600 with ultimate satisfactory results, but this is not to be recommended for beginners without some previous experience, and it is doubtful if there is any saving in either time or labour.

Scratches.

The last stage of fine grinding must be very thorough if satisfactory polishing is to be hoped for. Every minute spent on the last stage means time saved in polishing. Every charge should be thoroughly worked out with a steady short stroke. 600 is so fine that at first it may seem that no work is being done, and it is this that misleads the inexperienced. Work each charge out for the full five minutes, adding a spot of used mixture from the tray with plenty of water from time to time to prevent sticking

Minute scratches and pits left from previous stages are very difficult to detect even for an experienced eye, but they will show up glaringly whenever polishing is begun and may mean hours of extra work to polish out So the remedy is to do the last stage carefully and thoroughly, and work out the last charge to the limit

As a final grinding, a fine settling of flour emery may be used, and in fact is advisable, as emery leaves shallower pits in the surface of the glass than carborundum, and will therefore polish out quicker

Take ½ lb of Oakey's fine washed flour emery and mix in a gallon of clean water in any convenient round deep container Stir up vigorously until sure that all the powder is thoroughly mixed, and let it settle for two minutes; then pour off all the liquid into another vessel, leaving the settled sediment behind This liquid contains the emery which is fine enough for the finishing stage Allow it to settle for one hour and again pour off the liquid into another container, keeping the sediment. Use this for the final grinding. If

desired, a final settling of emery may be further taken from the liquid and used for yet another stage of finishing Two stages of emery are not compulsory, but experience has proved them a benefit in most cases, as an aid towards quicker polishing, though a properly finished surface from No 600 carborundum will polish quite satisfactorily.

Seizing.

During the final stages of grinding, the surfaces have become so smooth and well fitted that there is a great tendency for them to stick together or seize when the water between them works out. If the worker has the misfortune to have this occur, great care will have to be used to prevent damage to the edges of the glass The first thing that generally happens is that the handle comes off during the attempts to separate the two Avoid this if possible, as it takes away the one source of leverage when it is most needed. If the seizure is not too bad, an application of water round the edges may be enough, the mirror at the same time being tapped on the edge with a piece of wood and a hammer, with someone near to catch it when it separates A bad case may take hours for the water to penetrate between the close set faces. Don't attempt to wedge or lever the glasses or irreparable damage will be done to the edges Immersion of one glass in cold water may sometimes be successful Similarly, warm water may be tried alternately with cold water As a final resort both mirror and tool may have to be left in a pail of water for hours, or even days, before the water will penetrate sufficiently to allow them to slide apart.

Final Washing Up.

Before leaving the subject of grinding, a word on the final wash up preparatory to polishing. The process of polishing is entirely different in so far that it is a polishing medium that is used in place of cutting abrasive, so every trace of the latter must be got rid of before successful polishing can

be expected. An extra thorough wash up, therefore, must be undertaken and all trace of abrasive or grit eliminated. Some workers use a different barrel for polishing, and in some cases the grinding is done in a different room altogether. This is good practice if the worker has the accommodation available. A room for polishing should be, as far as possible, at a steady temperature and free from draughts, which may convey dust. Certainly there should be no fire burning if serious work is projected. The ideal room is one in a basement, below ground level, with thick walls and no window. If there is a window it should preferably face north and be capable of being shut tight. This is the perfect arrangement which can seldom be attained by the ordinary amateur, but he should get as near to it as circumstances will permit.

A light wood or corrugated structure may do for grinding, but is useless for polishing and testing, as it can never remain at a steady temperature. The majority of houses have an odd room which has no fire burning and which could be utilized for polishing and testing—the grinding preferably being done elsewhere.

CHAPTER V

Polishing

Theory.

The polishing of glass, to anyone outside the glass and optical trades, has always been an obscure and mysterious business. Information on the subject has always been difficult to get, and published literature very scarce. The few books about glass working that have been published are now out of print as well as out of date.

The theory of glass polishing is still rather obscure A certain amount of research has been done on the subject, and two theories have been advanced as to the action of the rouge on the glass. The first holds that the rouge particles act as tiny cutters, which plane the glass away till it leaves a polished surface In the second theory the rouge acts as a sort of burnisher and causes the molecules of glass to flow and fill up the rough or porous surface left by the grinding.

Principle.

The principle of polishing glass by hand is similar to grinding, but, in place of carborundum, rouge is used, and a tool of pitch instead of glass. Various other substances will act as carriers for the rouge with varying degrees of accuracy and speed of polishing Felt and certain kinds of cloth are used to a great extent by the trade, chiefly for polishing spectacle lenses and the cheaper varieties of optical work The grinding of small lenses up to 2-in diameter or so is done on fast revolving cast-iron tools of the correct curvature and about three times the diameter of the lens. During grinding, the lens, which is cemented to a small metal holder, is moved radially across the diameter of the rotating tool by the operator, who applies abrasive and water at the same time For polishing, a piece of pitch is held against the tool as it revolves, and a piece of the special cloth is then placed on the top and pressed into contact with the tool by the fingers as the tool revolves Rouge and water are then applied, when a complete polish in a 2-in lens is reached in about five minutes The correct radial motion is usually applied to the lens by means of an arm operated by a crank or similar device. An expert operator can produce excellent work on the revolving tool by hand manipulation alone without the use of mechanical devices for imparting the radial or cross travel. Lenses produced in this way are quite good for low-power work, where the magnification used does not show up the slight imperfections of slightly wavy surfaces In

the case of telescope objectives and mirrors it is different, however, as they must be capable of standing a magnification of anything up to 300 or 400 times, and further, stars, being very minute points of light, show up variations of curvature more readily than any other known objects.

Among the other substances suitable as a carrier for rouge mention may be made of beeswax Among the American amateurs this is extensively used in the form of honeycomb foundation (H.C F.) such as is used by beekeepers in their hives It is supplied in sheets moulded in the familiar honeycomb formation, and only the best quality is used. In use it is secured to the tool by a base of plaster or pitch and moulded to the curve of the mirror Its action in polishing is much faster than pitch, though the optical surface produced is not just so perfect, and it has the merit of being easier to use, inasmuch as it does away with the necessity of making the troublesome pitch tool Fuller information on its use may be obtained in American literature on the subject.

Tempering the Pitch.

With a properly made pitch tool and ordinary care, a high-class optical surface may be produced in from 4 to 6 hours, according to the state of surface left after fine grinding. The making of the tool is an important job, and to the novice may appear rather difficult at first sight The tempering of the pitch or judging the degree of hardness may perhaps be the most troublesome part of the process, but a certain amount of latitude is allowable Pitch is a very eccentric substance in its behaviour, and no two pitch tools can be relied on to perform in exactly the same way, even when made from the same pitch mixture Even an experienced worker cannot tell exactly how a newly made tool is going to behave until he has tried it out The moral is, once you have a good working tool, take care of it until you have finished with it A soft tool polishes quickly, but it is liable to produce a turned down edge, of which more will

be said later A hard tool polishes more slowly, but is more liable to scratch It seldom gives a turned edge, and for this reason most workers prefer to use a tool on the hard side The idiosyncrasies of pitch may be made much less troublesome by the addition of 10 per cent to 20 per cent of pure beeswax This pitch-wax mixture was strongly advocated by that experienced and enthusiastic amateur, the late Rev William F A Ellison, whose idea it originally was Care must be taken to stir the pitch and wax well, to ensure them being properly mixed The addition of the wax has the effect of reducing the stickiness of the pitch, a point which will be found beneficial when it comes to trimming the tool and cutting out the V-grooves A tool of this mixture may vary a good deal in hardness and still work satisfactorily

The hardness of the pitch or the wax-pitch mixture is perhaps one of the most difficult things for the beginner to judge When cold, the pitch should be just soft enough to be marked with the nail and no more If the nail digs into it readily it is too soft. Another test is to pour some on to a piece of paper and lay aside on a cold surface at room temperature, until it has properly cooled If it snaps when bent slowly it is too hard, but if it will not snap no matter how quickly it is bent it is too soft It should be just possible to bend it fairly slowly without snapping, until it is almost double, when it should snap Test by bending one way only, as it will certainly break if bent back again A strip about 1 in broad and about $\frac{1}{8}$ in thick is about right for the above test If too thick it may snap more readily and give a false impression of hardness Also make sure that the test strip is quite cold, or it may be misleading.

As previously mentioned, pitch may be softened by the addition of turpentine or hardened by prolonged or overheating. A small quantity of turpentine only should be added at a time. About half a teaspoonful will make a big difference to the degree of hardness of half a pound of pitch. If it should be made too soft, it may be hardened again by

heating up slowly until fumes begin to rise Allowing the pitch to remain melted on the stove for a prolonged period also tends to harden it, so it is advisable to make a test just prior to pouring it on the tool. The container in which the pitch is melted should always be heated gently at first, and it should never be set on a gas which is turned full on, or the fierce heat may cause an accident. A pot in which previously melted pitch has set should preferably be heated up the side first to enable the melted pitch from the bottom to escape owing to expansion.

Making the Tool.

The operation of making the pitch tool consists simply in covering the glass tool used in grinding with a layer of pitch and cutting V-grooves in it to form squares For those whose patience is limited and whose ambition does not extend beyond a mirror of medium perfection, a tool may be made very simply, which will produce quite a good mirror for low power A band of wet paper is first bound round the edge of the glass with string or adhesive tape A drop of turpentine is smeared over the face of the cold glass, then pitch to a depth of $\frac{3}{8}$ in is poured on When it is cool enough to keep its shape, a ruler well dipped in water is used to make grooves, much in the same way as when making toffee squares Keep on pressing the ruler into the grooves, renewing the water to prevent sticking, until they are clean and sharp and the pitch is set hard enough for them to keep their shape One inch squares will be about right for a 6-in. mirror, with the grooves about $\frac{1}{4}$ in. deep While the squared pitch is yet soft the mirror (previously coated with rouge and water of about the consistency of thick cream) is placed on top and worked back and forward, and at the same time turned round and round in order to mould the tool to the shape of the mirror curve If the pitch has been allowed to become rather firm, pressure may have to be applied Keep on working until the squares, as seen through the glass, are making

contact evenly all over the glass Sometimes the glass has a tendency to stick to the pitch, even with a copious supply of water between the faces, but this may be helped by a smear of clean soap. Once the pitch is cold, the glass will never stick if the faces are kept wet with rouge and water.

With a tool made in this manner, polishing may be carried on to a finish, and the mirror silvered and mounted without recourse to testing in any form Such a telescope may turn out very well, but at worst it will show excellent low-power views of the moon and the star groups, and be a source of delight to those for whom it is intended—those of limited patience The writer's experience is that the exacting job of making a high-class mirror with a good parabolic figure, at a first attempt, requires more than an ordinary degree of patience The difficulties and discouragements encountered during figuring are apt to be too much for the beginner and the task is given up before he reaches the stage of seeing the result of his work, but if he first follows the simple method described above, the encouraging result of his labours will probably impel him either to go on to correct the mirror's faults and parabolize it, or to make a new one by more exacting methods, the experience gained standing him in good stead

The making of a pitch tool for more serious work presents additional difficulties and needs more attention to details In general the method is similar to that of making the simple tool The glass tool is smeared with a drop of turpentine and left in readiness When the pitch has been tempered to the judged hardness, a layer is poured over the tool, starting at the outside edge and working to the centre in rings, adding an extra depth right in the middle The thickness at the edges should be about $\frac{1}{8}$ in., and slightly more in the centre. The pitch will flow over the edges and down the sides, but this can be trimmed later, and if it is not too hot no difficulty will be experienced in getting a thickness of $\frac{1}{8}$ in The wet paper band round the edge may be used if preferred, as in making the simple tool, but it should not be of too stiff a

paper or it will have to be removed to get a properly moulded surface Immediately the pitch has been poured on, lift the mirror, which has been previously coated with a thick layer of rouge and water, and place on top, immediately sliding and turning it about in all directions, until the pitch is firm enough to retain its shape, which will not take long with so thin a layer The chief difficulty here lies in preventing the hot pitch from sticking to the glass Keep on the move right from the start, and avoid heavy pressure as long as the pitch is fluid. A smear of soap before the rouge is sometimes a help If the pitch has been poured too hot, sticking is almost certain if pressure is used at the start If the first attempt is a failure, scrape the pitch off and try again

The whole operation is rather tricky, and failure to get an even curved surface at the first attempt should not be taken too seriously, as even experienced hands sometimes fall short and need a second trial A perfect moulded surface can very seldom be obtained, but if it does not contain any large areas of bad contact, and only a number of small air bubbles, not larger than ¼ in. diameter or so, it may be regarded as satisfactory, any small blemishes working out during polishing

Cutting the V-Grooves.

Before the moulded surface becomes too hard, the grooves or facets must be marked out with a small tool, consisting of a piece of wood with two strips of metal screwed on the sides, as shown in fig. 7 The size of squares may be anything within reason, but they must not be concentric with the centre of the tool. 1-in or 1¼-in squares for a 6-in. or 7-in. mirror, and 2 in for an 8-in mirror and upwards, will be satisfactory. The position of the squares has a very

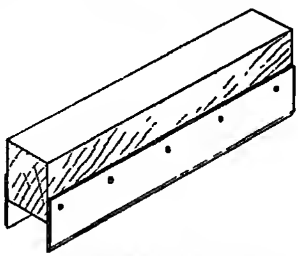


Fig 7—The marker used to mark off the pitch preparatory to polishing

important bearing on the behaviour of the tool during polishing. If the squares are disposed concentric with the centre of the tool, the mirror will polish in a series of rings instead of a regular smooth curve All symmetrical arrangements have the same effect, giving a symmetrical result The symmetrical repetition of the cycle of operations with a grinding or polishing machine is a case in point. Before marking off the squares, find the centre of the tool with a pair of dividers

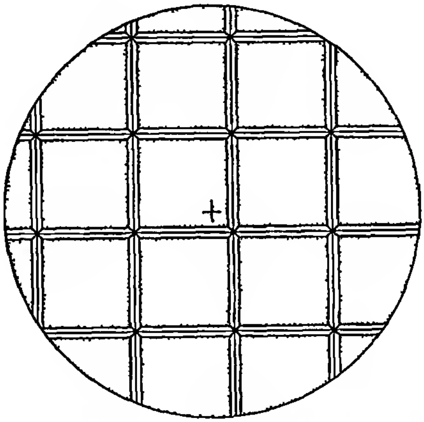


Fig 8 —A pitch tool with the V-grooves cut out ready for polishing

and make a mark Now this point must not be in the centre of a square, nor must the grooves cross at this point. Fig 8 should make this clear

The marker (fig. 7) is not for making the grooves, only for marking the surface of the pitch Start at the middle of the tool, pressing the marker firmly on the still soft pitch, tilting edgeways, so as to mark right across the curved surface, until a visible shallow groove is left. Make the line nearest the centre about $\frac{1}{4}$ in distant if 1-in. squares are used, or $\frac{1}{2}$ in for 2-in. squares, and the division should finish right. When the system of lines has been satisfactorily marked,

the next step is to cut V-grooves in the pitch right down to the glass An old razor blade may be used for this, but a better way is to saw out grooves with a clean hack-saw blade and then cut to a V with the razor blade Plenty of water should be used with the blade when sawing, and no trouble will be experienced. While the outside grooves are being sawed, the pitch is very liable to break away, so gentle pressure on the saw with plenty of water should be used.

Ensuring Contact.

During the cutting of the V-grooves the curve will have been slightly disturbed, as can be seen through the back of the mirror when it is placed on top of the tool If the pitch is still soft, the mirror, with a good supply of rouge and water, should be worked on the tool in all directions, and at the same time turned round and round Pressure will have to be used if the pitch is very hard If it is too hard the surface can be immersed in hot water for a minute or so to soften it sufficiently to ensure every square making contact. After a few minutes' work, the mirror should be making good contact all over its surface and is now ready for polishing.

Polishing.

The tedious job of making a pitch tool becomes fairly easy after the experience of making the first one, and any care bestowed on its making is well rewarded by the fact that polishing will proceed satisfactorily Polishing is carried on in the same way as fine grinding, using the three motions and two-thirds or one-half stroke If the pitch is known to be on the hard side, two-thirds stroke may be safely used for a time, without fear of anything drastic happening. If not sure, use a slightly shorter stroke for safety. Polishing, though not difficult, is perhaps more tiresome than other operations, as it will take from four to six hours to complete. It need not be done all in one spell, in fact, polishing should not

proceed in spells of longer than half an hour, as will be seen later when temperature effects are understood. The large handle used for grinding may still be used for the first hour or two without risk of trouble, but it is advisable to change to a smaller handle towards the end of polishing, and that for two reasons First, a smaller handle gives a clearer view of the state of contact, and, secondly, with a large back plate there is a risk of the thick wood, if it is inclined to warp, having a distorting effect on the glass sufficient to cause trouble.

The rouge should be mixed up with the water to the consistency of a thick cream and applied to the face of the mirror with a flat 1-in camel-hair brush A glass container, having a glass cover, or piece of glass on top, is best, and it should always be kept covered when not in use to exclude dust, which is the polisher's greatest enemy Each application of rouge should be well worked out with frequent additions of water After the tool has become charged with rouge, every second application may consist of plain water painted on the tool. The accumulated rouge in the V-grooves is thus brought into use, preventing clogging, and there is also a saving in rouge Glass polishes more quickly when the tool is kept wet with plenty of water Thick rouge polishes much more slowly, though first impressions may point to the contrary After two half-hour spells at polishing, the centre of the mirror should appear to have a fairly good polish

The centre polishes first for the same reason that the centre ground away first, during rough grinding. The outer edge is always the last to take the polish, and it is from it that the state of polish should be judged. By now any serious scratches or other defects will be very plainly visible, but if they are not too deep they will disappear by the time polishing is complete A sure way to detect scratches is to hold the mirror at an oblique angle on a level with the eyes and catch the reflection from a bright light or from the sky, when the scratches will stand out clearly.

At this point the worker will be desirous of seeing how the pitch tool is going to behave and what is happening to the curve of his mirror, so some explanation of the method of testing will be welcome.

CHAPTER VI

Foucault's Shadow Test

Foucault's Method.

In the days of Newton and Herschel speculum making must have been rather a difficult and trying occupation. Those workers had to work in the dark, up to the point when the speculum was mounted and trained on a star, before they could see the result of their work. The present-day mirror maker, be he amateur or professional, can actually see and follow the progress of the state of the curve, right from the moment that there is sufficient polish on the glass to reflect light For this, thanks are due to that celebrated French physicist, Léon Foucault, who was born on 18th September, 1819, and after a distinguished career died on 11th February, 1868 During the course of his optical experiments he evolved the ingenious method, now universally used, and known as " Foucault's shadow test " or sometimes " knife-edge test ".

The ordinary individual has always great difficulty in realizing the extreme delicacy or sensitiveness of Foucault's shadow test. It is this delicacy that is the stumbling block for beginners. Perhaps the reader may grasp its significance if he reflects for a moment on the fact that variations of radius of curvature of 100,000ths of an inch are being seen and interpreted. Even the slight expansion caused by the heat

from the finger touching the glass for a moment is sufficient to show as a decided lump on the surface of the curve. In the opinion of some the test is unnecessarily delicate for ordinary work, but that depends on the user's ability to understand and interpret the shadows A test on a star will show exactly what this ability is worth

The apparatus for Foucault's shadow test is simply a small pinhole lamp and a knife edge, with some means of holding the mirror during the test.

The Lamp.

The pinhole lamp, as its name implies, is a lamp with a chimney or funnel in which a pinhole has been pierced Any convenient form of illuminant may be used, but the simplest and perhaps the best is a small oil or paraffin lamp The lamp must be small in diameter so that the knife edge and pinhole may be brought together as close as possible The container should not be more than 1½ in or 2 in. diameter and the chimney about 1 in diameter. A very convenient lamp can be made with a burner from an old motor-car oil side-lamp Such a burner is very suitable when fitted into a small tin container for the oil (paraffin), and as most patterns are designed for fitting into plain sockets, no difficulty should be experienced in finding a suitable tin to fit There is no need for a glass chimney, as one made from a piece of sheet tin answers admirably if bent round a mandrel of the correct size A small hole about the size of a medium sewing needle should be pierced opposite the middle of the flame If the tin is filed almost through with a fine file, the needle will pierce the funnel without much difficulty. A smaller hole may be made at right angles for finer testing If preferred, a ½-in hole may be made in the chimney, and sliding tin covers made to fit over the large hole with various sizes of pinholes

Electric light may be used if precautions are taken to ensure even illumination of the pinhole. A small tubular

lamp is the most suitable, but it must be opal to diffuse the filament A pearl lamp would do for rough testing, and a thin opal screen might be interposed for finer work A tin chimney and a pinhole must be used with this just as with the oil lamp It is advisable to leave clearance between the lamp and funnel for an air passage, or it may become unpleasantly hot It must be remembered that this lamp is being used in comparative darkness, and there is a risk of getting a disagreeable burn on the point of the nose by accidentally coming against it A piece of thin sheet asbestos wrapped round the chimney is a good safeguard against this happening

The Knife Edge.

Various ideas for the knife edge have been evolved from time to time; some of them good Essentially it consists of a metal straight edge, with one side filed to a sharp edge, and fixed to a substantial base Fig. 9 shows quite a serviceable knife edge, along with an oil lamp, as used by the writer. The blade may be a piece of steel, brass or even zinc, about $\frac{1}{32}$ in thick, soldered to a thick metal base made from any odd piece of brass, about $\frac{3}{8}$ in thick and 3 in long by 2 in broad or thereabouts, with two opposite edges filed straight It will be noted that the knife-edge blade is cut away to enable it to get close up to the lamp, a convenience which is useful, though not absolutely necessary. Some very elaborate arrangements are marketed in America for the amateur. Some of the more expensive types are a combination of knife edge and electric pinhole lamp in one unit, with every

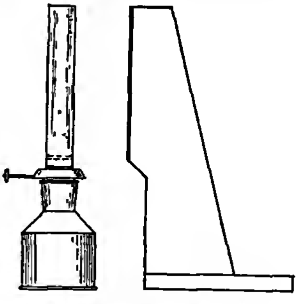


Fig 9—The pinhole lamp and knife edge

possible adjustment mechanically operated The lamp can be raised or lowered and the knife edge operated by micrometer screws in all directions Such elaboration may be very convenient, but it is doubtful if it will show any advantage in practice over a plain hand-manipulated outfit

The Easel.

Another simple but necessary fitment is required to hold the mirror steady and safe during testing This may consist of a right-angled wood bracket, with a V-block to hold the mirror steady and a slot cut away to clear the wood handle Some means of adjustment for level is necessary in order to get the reflected image of the pinhole to coincide with the pinhole itself Fig 10 is self-explanatory

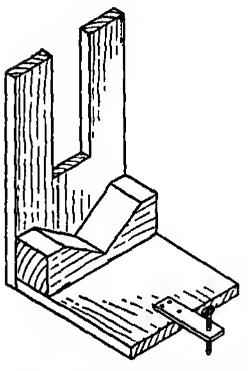


Fig 10 —Stand for holding the mirror during testing

Another very convenient method for holding the mirror is to hang it on the wall This method is particularly useful where difficulty is experienced in finding a steady and rigid support for the mirror easel Walls generally are rigid and free from vibration, except in towns when heavy traffic is passing, in which case testing is out of the question altogether A metal band of thin sheet brass or zinc, cut a little broader than the thickness of the mirror and clipped with a screw and nut to form an easy fitting ring round the mirror, can be hung on a strong nail at the most convenient point for testing Spacing strips will have to be fixed to the wall to give clearance for the handle and to ensure the mirror taking up the same position each time it is hung up. Such an arrangement, when once fixed up and set in alignment with the lamp and knife edge, has the merit of being free from vibration and of

being easily replaced in its original setting, relative to the knife edge.

Principle.

To grasp the principle of Foucault's shadow test thoroughly, a study of simple optics will be necessary When the rays of light from a pinhole are collected by a spherical mirror they are reflected back to form an image of the pinhole, at a point dependent on the curvature of the surface and its distance from the pinhole If the pinhole be at infinite distance this point will be the principal focus of the mirror, which is half-way from the centre of curvature to the surface, but if the pinhole be at the centre of curvature the image of the pinhole will reflect back exactly on itself To repeat the figures for the 6-in mirror, as given in a previous chapter, if the principal focus (or focal length) is 48 in , then 96 in will be the radius of curvature, or the distance at which the lamp must be placed for testing in this case

With the image of the pinhole focussed on itself, it is not possible to examine it directly with the eye, so Foucault moved the lamp a little to one side, thereby moving the image in the opposite direction In this position it is now possible to examine it directly with the eye or other means. Difficulty may be found at first in getting the eye on the illusive spot of light, but its position may readily be discovered by means of a piece of white paper held up behind the lamp, or a torch may be first used (as when testing for radius of curvature during rough grinding) to locate the approximate positions of lamp and mirror, and then the naked light of the lamp itself focussed on the paper and carefully adjusted to the same level

Fig 11 shows the relative positions of the mirror, lamp and knife edge, ready for a test A is the lamp, B is the knife edge, C is the mirror, and the eye sees the image at D* The knife edge should be as near the lamp as can be conveniently

* In practice the eye is kept close to the knife edge

arranged for comfortable working, and for the later stages of finer testing the closer the better With the naked eye, no image of the pinhole will be seen, but only the fully illuminated disc of the mirror If only a small disc or spot of light is visible, move the lamp nearer or farther away from the mirror until the disc of light appears the full size of the mirror, when it should be at maximum brightness

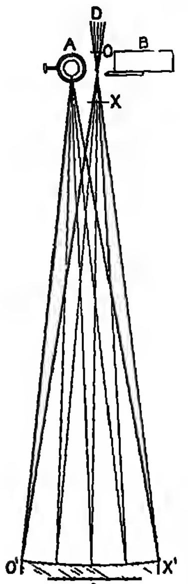


Fig 11 —Principle of Foucault's shadow test

Keep the eye in this position (not very easy at first) and slide the knife edge gradually across, so that it begins to cut off the beam of light entering the eye Now watch carefully for the outcome of Foucault's ingenious method. If the knife edge is about 1 in nearer to the mirror than the focussed pinhole image or centre of curvature, a sharply cut black shadow will be seen to move across the illuminated disc, uniformly with the movement of the knife edge and in the same direction, until the whole disc is blotted out. If the knife edge is beyond the centre of curvature by the same distance, the shadow will move in the opposite direction to the knife edge. The reason of this may be seen by reverting again to fig 11 Suppose the knife edge to be entering the cone of light at X, it will begin cutting off the light coming from X′ on the same side of the mirror as itself, and so the shadow will appear to travel with it. With the knife edge entering at O the light from O′ is cut off first, and the shadow, therefore, will appear to enter from that side and travel to meet the knife edge or in the opposite direction.

Characteristic of a Sphere.

The nearer the knife edge is to the point of focus the less

sharp or more diffused the edge of the shadow becomes When it cuts the cone of light exactly at the point of crossing of the rays, the light from the mirror, if it be a true sphere, will gradually disappear as the knife edge is moved across, or, in other words, will slowly darken down until only the black circle of the disc remains visible This is characteristic of a true spherical curve The explanation of this may be taken to be simply that at this point the knife edge is cutting all the reflected light at the point of crossing of the rays, being neither within nor without the focus, and so is at a neutral point showing no distinct shadow entering from either side, but a diffused shadow entering evenly all over, or an even darkening of the surface A thorough memorizing of the principles of the shadow test as applied to a truly spherical curve is advised, if the reader is to understand and apply it to the complex and irregular curves dealt with in the next chapter

CHAPTER VII

Preliminary Testing

The Spheroid.

The first examination of the mirror, which has been polished for two half-hour spells as described in Chapter V, will probably prove rather disappointing and confusing after studying the previous chapter This is as should be expected A truly spherical curve is very seldom met with at the first test, but if by an extraordinary stroke of luck it should, the probability is that it will have changed long before polishing is complete Polishing could be carried on right to the end before any testing at all is done without anything serious happening that could not be remedied later, provided, of

course, that orthodox methods were adhered to Beginners are advised not to adopt this course By testing after every half-hour spell, the beginner is enabled to satisfy his curiosity and become familiar with the various complex curves or figures as they appear

Familiarity with the different types of figures enables the worker to apply the various remedies and methods more effectively for their elimination and prevention. Further, the practice in using the knife edge itself will help him to cultivate the delicate touch necessary for the final testing of the parabolic curve It is important to bear in mind from this point onwards that the ultimate figure aimed for at the end of polishing is a spheroid, or spherical curve, which is a starting point for the paraboloid.

On Keeping Records.

From the previous chapter the method of testing at the centre of curvature should be clearly understood. Its practical application will now be dealt with during the remaining stages of polishing One of the first things to be impressed on the worker is the importance of keeping records of all the tests made and the type of figure seen at each The keeping of records is a natural habit with some people, but others require to develop it To acquire the habit during this stage is something which will never be regretted, if full use of the finished telescope is to be made. The keeping of records of all observations made, and what is seen at each, is the first step towards becoming a successful observer. Also if subsequent mirrors are to be made, the mine of information which such records contain will be found invaluable.

One very convenient way of keeping records is in a tabulated form under such headings as time, pinhole, shape of curve, remedy and remarks.

Visual Interpretation.

Right from the beginning an attempt should be made to interpret the visual impression of the curve, as seen with the knife edge at the exact point of focus. This may prove to be rather difficult, as visual impressions vary greatly with different individuals When a truly spherical curve comes under the knife edge it darkens down evenly, as has been already explained, but the impression it makes on the mind is that the surface is flat, not curved It may be put down in the records as a straight section A spheroid always appears flat under the knife edge, or in other words this particular curved surface visually is changed to a flat one It follows, therefore, that any variation from this curve will show itself in a corresponding change from the flat appearance. Here one further difficulty may perhaps present itself with a complex curve, viz that of telling exactly whether certain portions are raised above or below the spherical curve (flatness), or whether they are hills or hollows The simplest way of deciding this is to press the finger on the centre of the glass for a few seconds until it expands, and then view it immediately, when the characteristic appearance of a hill will be seen Sometimes, even after some experience, it may be difficult to decide whether a small portion right in the centre is a hill or a hollow, but this simple dodge will settle the point immediately Occasionally an optical effect, which might be described as " reversed vision ", is met with during testing, in which the appearance of a hill is reversed or looks like a hollow. The same effect may be got by placing the knife edge on the left-hand side instead of the right In fact the knife edge should be tried both ways on the finger-test dodge, and that side used which shows the expanded portion of the glass as a hill rising out of the general surface, as the writer has come across people with vision opposite to his own. Fatigue and eye strain may set up reversed vision after prolonged testing This phenomenon occasionally occurs

with some people, during a prolonged observation of the moon, while others have never experienced it at all

Plate III shows six photographs taken from drawings made by the writer in an attempt to convey to the reader the appearance of the knife-edge shadows

Fig 1—The shadow of a figure roughly parabolic with the knife edge at the mean centre of curvature (i e beyond the centre zone and within the outer zone) The knife edge is advancing from the right-hand side If the knife edge is used on the left, turn the page upside down to see the shadows in their correct positions The reader should attempt to grasp the characteristic appearance of a hill and a hollow A careful study of figs 5 and 6 should convey the impression that the centre of fig 5 appears raised and that of fig 6 hollow If the page is turned upside down they will appear vice versa In the other four figures the raised or hollow appearance is not so pronounced but after a little practice it should become apparent

Fig 2—Oblate spheroid or a spherical curve with a " flat centre "

Fig 3—A small hollow in the centre often caused by the heat from the hands being transmitted to the glass by the handle

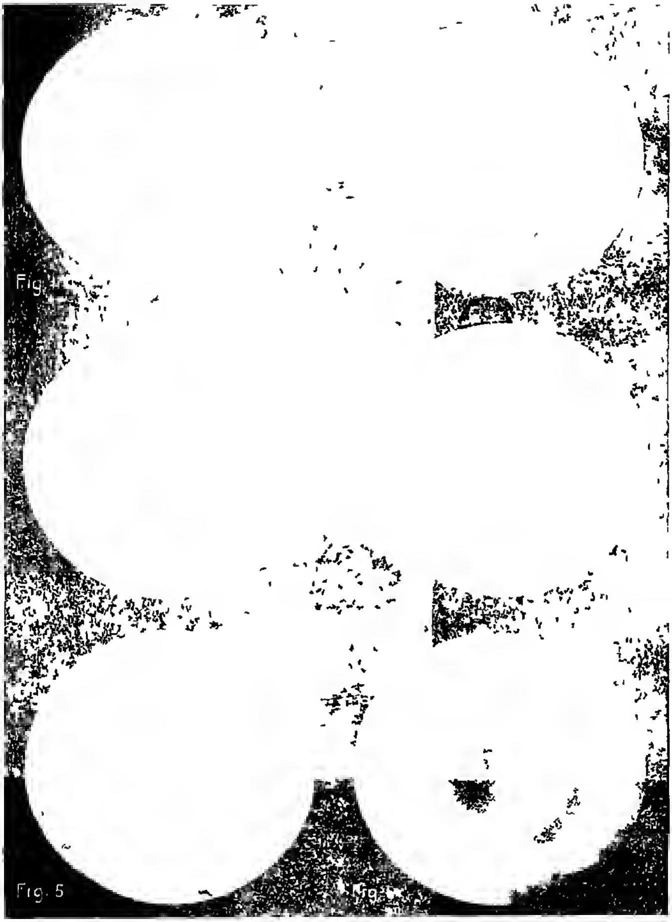
Fig 4—A small hill in the centre.

Fig 5—An irregular figure showing a large hill in the centre surrounded by a raised ring

Fig 6—An irregular figure showing a large hollow in the centre surrounded by a hollow ring.

Keeping Contact.

Let us return to the subject of polishing, and consider the different types of figures and defects met with, together with the various means available for their elimination and avoidance. If polishing has been carried on in short spells, with short strokes, not more than half-stroke, in a room of fairly constant temperature, the curve should be reasonably near a sphere



Shadows

1 Paraboloid 2 Oblate spheroid 3 Hollow in centre 4 Hill in centre
5. Hill and raised ring 6 Hollow and hollow ring

Facing p 46

provided sufficient care has been taken to ensure good contact. Before any spell of polishing is undertaken be sure that the mirror and tool are in contact evenly over all the surface. During a break in polishing, even for a night, the pitch will have slightly changed its shape It should be remoulded by heating the surface of the pitch by immersion in hot water for a minute or so and working the mirror with pressure, until contact is assured, thereafter leaving the two in contact for a short time, until they have cooled to the temperature of the surrounding air Care must be taken that the mirror does not accidentally slide off A loop of cardboard of the necessary breadth placed loosely round the two is a good safeguard Strict attention to maintaining contact, with a reasonable tool, and the exercise of common sense with regard to temperature conditions, should produce a figure at the end of polishing which will need very little manœuvring into a good spheroid. This is the secret of successful work, both for the beginner and the experienced hand

Turned Edge.

If through the prolonged use of too long a stroke or the use of a tool of too soft pitch, the worker has produced what is known as a turned-down edge, how is he to recognize it? The knife edge will almost certainly fail to show it unless it be excessive, but an out of focus image seen through an eyepiece will detect it almost immediately The eyepiece may be affixed to the opposite side of the knife edge by a clip-on arrangement capable of being adjusted for height, or it may be a separate piece of apparatus altogether. Any common eyepiece of ¾ in or 1 in equivalent focus may be used In use the eyepiece is substituted for the knife edge, and the reflected image of the pinhole sharply focussed and adjusted to be in the centre of the eyepiece, an operation not just so simple as it may appear If the image of the pinhole is first set with the knife in position, and its height noted on the blade, the eyepiece may then be easily adjusted to suit On looking

into the eyepiece when accurately focussed, the actual image of the pinhole will be seen, magnified The lamp and eyepiece should have been previously set on a common base, such as a piece of thin wood or cardboard, so that they may be moved together By sliding them both about $\frac{1}{4}$ in nearer the mirror, the image will appear out of focus or diffused and larger in size If the edge of the pinhole still remains distinct or clean cut, there is no turned down edge If the edge looks fuzzy and indistinct, with a decided hairy appearance, the edge is turned down, i e instead of following the general contour of the curve of the mirror, it flattens out at the edge, or is less curved than it should be See fig 12, which shows a greatly exaggerated curve in heavy line. This is one of the most troublesome faults to remedy and entails a large amount of extra work To get rid of the turned edge a layer of glass must be removed right across the whole surface of the mirror, as is shown by the dotted line in fig 12 Removing glass by polishing is always a comparatively slow process, and with a badly turned edge may take hours, so the moral is apply the eyepiece test frequently and detect it before it goes too far If too long a stroke has not been used and the mirror has been kept travelling centrally across the tool, turned edge need not be feared, provided, of course, that the pitch has not become too soft, e g through too long working spells or a big rise in temperature of the workroom from that in which the tool was first made. If the tool is believed to be soft, remake it and keep it slightly on the hard side With a hard tool and short strokes about $\frac{1}{3}$ or $\frac{1}{4}$ stroke, a slightly turned edge may be brought right in a very short time A bad case had better be treated with a specially prepared tool, about $\frac{1}{2}$ in less in diameter than the mirror, of hard pitch Use short strokes, check up with the eyepiece and knife edge, and then return to a normal

FIG 12 —Exaggerated diagram of a turned-down edge shown by heavy curved line

tool. A grossly turned edge should never be allowed to develop to the extent of necessitating an under-sized tool.

Hills.

Perhaps the easiest trouble to deal with is a hill or elevated section of the glass in the centre of the mirror When only slightly pronounced, it could be more appropriately named a mound A hill always appears in the middle of the mirror. If it did not, something would be wrong with the sequence of operations or the glass is of uneven hardness

As a general rule, hills do not develop unless there is an area of defective contact in the middle of the tool, such as a large air bubble or damaged centre square The removal of a hill is a comparatively simple operation taking a matter of minutes only It is so easily removed that care is needed not to overdo it and leave a hollow instead, a much more difficult proposition The actual operation consists in using a mixture of side stroke and circular stroke or, as it may be called, circular side stroke Side stroke alone can be used with a little experience, but the addition of a circular motion tends to leave a more even curve with less risk of a deep hollow right in the centre Side stroke is similar to the ordinary, with the difference that instead of moving the *centre of the mirror* across the *centre of the tool* at each stroke, the mirror moves with its *centre near, or on top of, the edge of the tool* About a dozen strokes with the centre on the edge would remove quite a moderate hill right in the centre Test after each dozen strokes to see the effect, and vary the amount of side hang of the mirror according to the spread of the hill, or adopt a circular or elliptical motion in place of the straight back and forward strokes. After a few trials, testing every few strokes, the art of the removal of a hill should be quickly grasped. Rather stop short than go too far, as a few careful strokes at the end will put things right. Better a hill than a hollow for the final operation.

Hollows.

The removal of hollows is a much more difficult task, the necessity for which should be avoided by keeping a careful watch with the knife edge. Like turned edge, a large amount of glass must be removed to bring the surrounding surface down to the level of the lowest point in the hollow As hills are caused by bad contact, so conversely hollows may be cured The size of a hollow should be estimated while viewed under the knife edge, and an equal area of bad contact should be created in the tool This is done by very lightly scraping the surface of the pitch with a used safety razor blade, just removing the rouge and no more When polishing is carried on for a time with this tool, the hollow is not making contact in the centre and therefore tends to become a hill, causing a general levelling up of matters During this time the pitch tool has been coming back to full contact, and probably by the time the hollow is removed the tool is in full contact, ready to carry on polishing normally. If a test still shows the hollow to exist, the cycle of operations may be repeated, always remembering that a slight hill is preferable to a hollow

Temperature Effect.

Hollows are always difficult to avoid, and the writer's experience is that the heat of the hands is the main cause Those who suffer from hot hands will find most trouble in this direction, as will also the over-zealous worker who does not have an occasional break to let the mirror and the wood handle cool down. The heat from the hands is transmitted by the wood, after a time, to the glass, thereby causing it to expand in the middle, and so, this being the highest point, it will polish away first, thus causing a hollow when it contracts This local temperature effect may be rather deceiving, this being the first occasion on which the beginner has encountered an example of temperature change When the mirror is taken off the tool at first and examined

under the knife edge, everything may appear normal, nothing being too far out of place to warrant special measures, but if it is examined about 20 or 30 minutes later, a decided hollow will be apparent right in the centre, the glass having cooled down and contracted where it was previously expanded. Towards the end of polishing, strict attention will have to be paid to this point or trouble will be experienced in working up even to an approximation to a spheroid Test, certainly, after taking off the tool, just for interest's sake, but wait for 15 to 30 minutes before making a final test and decision on the state of the curve. The writer experienced great difficulty during his early attempts with a persistent hollow, always about the size of the handle, which was small and of a very hard variety of wood Hours of work were wasted in trying to cure this hollow, only to have it recur. Only after a long and laborious process of reasoning and experiment was the cause understood and eliminated A softer wood handle was substituted, shorter spells of polishing undertaken, and proper time allowed before testing, and then the trouble disappeared A similar case came to the writer's notice recently, in which a friend made use of a glass handle for the mirror The result was inevitable, as was subsequently seen under the knife edge, a nice hollow corresponding to the size of the handle

Rings (Plate III, figs 5 and 6).

Another troublesome fault for the beginner to remedy is a ring, either raised or hollow, the hollow ring being the worst to cure For rings caused through faulty tool construction there is no excuse, as for those caused through bad contact, well, they can be avoided with a little care and common sense The most common cause for the formation of rings is misjudgment when removing a hill or a hollow. When a hill is being removed, the radius of movement is, roughly, equal to the width of the hill, but if only the central portion has been worked on, a raised ring may be left behind

Frequent checking with the knife edge will show this, and the radius of movement should be increased or decreased accordingly. A raised ring may be left surrounding a hollow, after the hollow has been removed, through too large an area of pitch having been scraped away If the raised ring is only slight, it may be removed by the judicious use of a circular or elliptical stroke on the centre of the tool A bad case may require scraping away of the surface of the tool, leaving only a ring of untouched pitch of the same diameter as the ring on the mirror. By the use of short strokes and frequent testing, it may be easily eliminated The scraping away of the tool should be sparingly done for a raised ring, as it will come right very much faster than a hollow ring. The treatment for a hollow ring is the same as for a raised ring, only the scraping away of the pitch is reversed, a ring of only the size of the hollow being taken off As with the hollow, so with the hollow ring, polishing must be carried on until the surrounding glass comes down to the level of the bottom of the ring

The beginner will be well advised to make a careful study of each figure, as seen under the knife edge, taking plenty of time to make up his mind whether to carry on polishing or apply corrective methods If a hollow shows up, do not carry on too far before checking up to see if it is still developing Take preventative measures in good time, ere worse befalls A hill may be ignored for a time with confidence, knowing that its removal is a fairly simple matter A small hill may be removed by a small polisher of 2 in. diameter or so, held in the hand and used much in the same way as a French polisher uses his rubber. Here again there is a risk of overdoing it, so go sparingly and finish off on the main tool.

Lastly, there is always a reason for a defective curve, and if the cause can be located, the remedy will be obvious.

CHAPTER VIII

Parabolizing or Figuring

The Parabolic Curve.

In the last chapter the general testing of the mirror during polishing was dealt with only with regard to the checking of any bad faults which were likely to develop. By this time sufficient experience should have been gained in the manipulation of the knife edge and the interpretation of what is seen by the eye, to enable a beginner to proceed to the final or finishing stage, namely parabolizing. A good parabolic curve is a work of art, and the art can only be acquired by actual practice and patience, but the beginner should not be discouraged, because even a poorly parabolized mirror will show him something of the sky, and, if he uses his intelligence, he will see and learn more about its faults and defects than the knife edge alone can reveal. And, further, the difference between a spheroid and paraboloid is so very small that very little work is involved in "rubbing it out", so to speak, and starting over again.

Temperature Changes.

An observant worker will now have realized that his skill in seeing very minute difficiences in the curve of his mirror has undergone marked improvement Flaws which he could not see before now stand out glaringly. The curve of the mirror should by now have reached such a stage of accuracy that temperature changes will have an appreciable effect on testing The difference in the depth of any of the delicate shadows seen will possibly be so small that only the trained or experienced eye will be able to distinguish them, so any changes of temperature in the air surrounding the

mirror will cause disturbances of sufficient magnitude to show as changes in the depth of shadow In a room with a slight draught of warmer or colder air passing across the mirror, an effect much like that of passing clouds will be seen A damp cloth or a dish which has contained a liquid, if brought from another room of different temperature and placed near or alongside the mirror, will show a positive storm of changing shadows resembling clouds of steam passing across This effect is always of interest when one is showing friends the mysteries of the knife-edge test, and is easily seen even by the most inexperienced eye A human body near the mirror will also set up disturbances great enough to make testing impossible until the cause is removed, so delicate is the test The foregoing effects are more air disturbances than actual changes in the curve of the mirror The great importance of selecting a room with as steady a temperature as possible will therefore be fully realized

Irrespective of the direct effect of the changing air itself on testing, changing temperature will also show its influence on the glass of the mirror, more especially during parabolizing In a previous chapter the effect of heat transmitted to the glass by the hands was shown It becomes much greater now, and every precaution should be taken to reduce it to a minimum When the curve of the mirror has reached such a stage of perfection that no irregular shadows can be discerned, i e when the surface is a spheroid, the bending of the glass itself through changing temperature will have to be contended with As already mentioned in Chapter II, it is the bad conductivity of the glass that causes this bending or change of figure, so the importance of waiting until the glass has reached a state of equilibrium of temperature before testing will be fully appreciated The figure of a mirror, as taken off the tool, will become completely changed after a lapse of about 20 minutes This fact is brought about by the slight rise in temperature caused by the friction of the glass on the pitch, and it is during the actual process of cooling

that the glass bends or distorts, the outside surface cooling before the inside It does not in the least matter whether the temperature is 50° or 70°; no bending will take place if the air and the glass are equally warm. It is difference of temperature between the two which causes the trouble. The reader may think that this repeated mention of temperature troubles and effects is rather unnecessary and a waste of good paper, but the writer knows, from bitter experience, the disappointment and extra work which can be caused through lack of attention to this point A reasonably perfect curve can never be made without a proper understanding of this fact

As already mentioned, the figure finally aimed at, preparatory to parabolizing, is a spheroid or as near to it as possible There is no short cut to a paraboloid unless by chance methods, which never pay The surest way is via a spheroid, because then a perfectly regular curve is always assured, as there is no mistaking the perfectly flat appearance, and even darkening down, of a sphere, under the knife edge. With experience a parabolic curve may be arrived at from a figure approximately parabolic, but it takes an expert eye to interpret the shadows with any degree of certainty, so a beginner should not attempt it, or he will probably get into a hopeless mess

Study of Parabola.

Having eliminated all irregularities from the curve, such as hills and hollows or rings, and arrived at an approximation to a spheroid, we must now study the parabolic curve in order to fully understand the next step Fig. 13 shows a spherical curve A and a parabolic curve B. C is the centre of curvature where testing is done The principal focus is at F, and the dotted lines embrace the angle of the rays of light of a mirror, whose diameter (i e breadth) is $\frac{1}{4}$ of its focal length, or focus, and which is therefore described as F4. Although the difference between a parabola and a sphere is

very great, it will be seen that the difference between the small section used in an astronomical mirror (the paraboloid) and the spherical curve is very small indeed Actually the difference at the edges is so little that it would require to be measured in 100,000ths of an inch, not thousandths

A general glance at the two full curves will show that the parabola does not follow a circular path, but gradually deviates from it by straightening out, the curve becoming flatter as it proceeds outwards The operation of parabolizing consists in flattening out the curve of the spheroid in like manner In practice it is easier to slightly deepen the curve in the centre by the requisite amount than to flatten it out In deepening the curve, more glass is removed from the centre, and the amount removed gradually diminished until the outer edge is reached, where none is removed at all The difficulty in parabolizing lies in this—maintaining a gradually straightening curve from the centre right to the edge

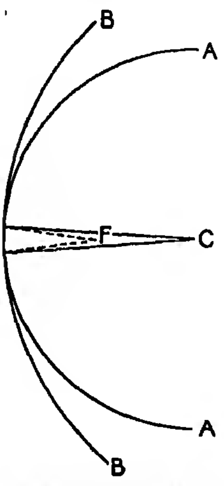


Fig 13 —Diagram showing difference between a spherical and a parabolic curve

The difference from the spherical varies with the F number At F4 the difference is not very marked, but at F12 the difference is so small that difficulty is experienced in checking it, even with so sensitive a test as the knife edge The explanation of this may be better understood by drawing two curves on a piece of paper, one representing a sphere and the other a parabola similar to fig. 13, and with the centre of curvature and focal point marked If the distance from the mirror to the focal point is 4 in., then at F4 the size of mirror will be represented by 1 in. or $\frac{1}{4}$ of the focus, and at F12 it will be $\frac{1}{3}$ in. or $\frac{1}{12}$ of the focus. If these sizes

are marked on the curves, the relative difference between the curves at F4 and F12 will be at once apparent.

Methods.

In parabolizing, the hardness of the tool has a bearing on its behaviour A tool of hard pitch tends towards creating a spherical curve If difficulty has been found in reaching a good spherical curve, a hard tool maintained in good contact and used with steady short strokes will greatly overcome this trouble On the other hand, a soft tool tends towards making the curve deeper in the centre or inclined towards the parabolic or hyperbolic A hyperbolic curve is of the same character as a parabola, only deeper If the depth of the paraboloid is carried too far, it will become a hyperboloid To the early workers, the hyperbola was incurable, as was a turned edge, but with a good hard tool and steady work it can be brought back quite satisfactorily. In coming back from a hyperboloid the curve has to pass through a paraboloid and it is worth while to test frequently, as with a suitable tool a good paraboloid may be arrived at, thus saving the work of going back to a sphere and working from there. As already stated, it takes an experienced eye to interpret the parabolic shadows with sufficient certainty to ensure a regular curve, free from zones, by this method, but its possibilities should not be overlooked even by the beginner.

Of the five most common methods used by amateurs at the present time, each has its own special advantages, and individual workers generally find one particular method specially suited to their requirements

Graduated Facets.

Parabolizing by graduated facets is perhaps the simplest method for the beginner, though it means altering the tool, a practice which the writer does not like, especially if the tool is a good one An alternative to altering a good tool is to make another one on a suitable base of the approximate cur-

vature Ellison strongly recommends this method of graduated facets in his book *The Amateur's Telescope* The V-grooves in the tool are gradually widened from the centre to the edges, after the manner of fig 14 The principle underlying the action of this tool is that there is less surface of pitch left at the edges than at the centre; consequently, the centre of the mirror will polish away faster than the edges, so that the curve tends to the parabolic form With short strokes and a suitably graduated tool, parabolizing is fairly easy, but the snag lies in making a properly graduated tool It is well to start with a medium amount of graduation, keeping a careful eye on the progress of the curve and increasing the cutting away, if necessary The success of this method depends on correct graduation If it is overdone it means making a new tool.

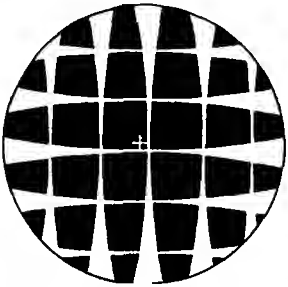


Fig 14 —Sketch of a graduated tool showing how the V-grooves are cut away from centre to edge + marks centre

Long Stroke.

Long stroke may be utilized as a means of parabolizing As was seen in the chapter on grinding, long stroke was used to hollow out or deepen the curve, and it is this that is used to advantage now The drawback to long stroke is its tendency to turned edge, and it must be used carefully and sparingly. In combination with other methods it is quite useful.

Side Stroke.

Side stroke can be used for deepening the curve, if care is taken to vary the amount of overhang and length of stroke and distribute it evenly over the surface This method used alone can yield good results with experience, but it can be

rather dangerous in unskilled hands, as a deep hollow can be very quickly developed in the centre by working too much in the same position By careful study the proper distribution can be roughly estimated, and tests made with the knife edge as a check, and adjustment made accordingly

Circular Side Stroke or Elliptical Stroke.

The method the writer favours and uses may be termed *circular side stroke*, really a combination of side stroke with a circular motion If a circular motion has been tried out in removing a hill, it will be apparent that its action has a decided smoothing or levelling effect on the small irregularities nearly always found near the middle of the mirror By suitably combining and mixing the circular motion with side stroke, varying the amount of side or overhang so as to remove slightly more glass from the centre, very quick results can be obtained

To use this combination effectively, it must be borne in mind that the aim is to deepen the curve slightly more in the centre, gradually tapering off to nothing at the edges in a smooth even curve About half a minute's work at a time is all that should be attempted at first with this stroke before a test is made, remembering to allow long enough for the curve to settle to its final figure each time. Only by frequent testing can control be exercised, and should the curve tend to become too deep right in the centre, or irregular, reverting to ordinary short stroke for a short time will help to bring it back within reason If frequent testing and allowance for temperature are neglected, things may have gone so far wrong that drastic remedies may be needed to put matters right This applies to any method of parabolizing used with plate-glass With pyrex, temperature does not have the same effect and shorter time can be allowed for the mirror to reach a state of equilibrium. With the short spells on the tool at this stage the waiting time for pyrex can be almost disregarded, unless the worker has very hot hands.

Small Polisher.

After a little experience in keeping control of the figure, a small polisher down to half-size may be used The small polisher, if used intelligently, with varying lengths of stroke, can be very satisfactory, but it is not to be recommended to beginners without some experience of other methods It is very useful to have a small polisher made up on a separate base for working on the centre of the mirror when required Used with one length of stroke only, the small polisher has a tendency to upset the even flow of the curve, but if the length of stroke is varied, a fairly regular curve should result.

CHAPTER IX

Measuring the Paraboloid

Parabolic Shadows.

So far, in order to avoid confusion, the characteristics of a parabolic shadow have not been considered A characteristic shadow is shown on Plate III, fig 1 A careful study of this is advised, but allowance must be made for the loss of the finer shadow detail in reproduction. The shadow of a hyperboloid is very similar to that of a paraboloid, but the shadows are deeper or more pronounced

Experience is the only guide to the interpretation of the shadows, but if the curve is free from obvious defects and shows a regular even shadow, similar to those in the illustrations, the beginner cannot go far wrong, because, as will be seen later, he has a definite check in direct measurement.

A parabolic shadow is rather difficult to describe without an actual demonstration with the mirror and the knife edge.

It must be borne in mind that the knife edge, when it cuts the reflected rays of light exactly at the centre of curvature, shows a darkening down, or shadow As a paraboloid will focus only parallel rays of light to one point, it follows that the diverging rays coming from the pinhole, when reflected from the centre, will come to a focus at a different point from those reflected from the edges, through the slight difference of focus between the centre and the edges, owing to the flattening curve of the parabola If the knife edge is at the centre of curvature of the central part of the mirror, it will darken down there first, or show the shadow of the knife edge stationary The edge being of longer focus, the knife edge will therefore be within the centre of curvature of this zone and will show a shadow travelling in with the knife edge, as explained in Chapter VI With the knife edge at the centre of curvature of the edge, both edges will darken down together and the centre will show a shadow moving across in the opposite direction to the knife edge. In this position the centre shadow must move opposite to the knife edge, because it (the knife edge) is beyond the centre of curvature of the centre zone By simple reasoning on these lines any type of complex shadow may be interpreted and understood In fact it is the only way, short of a practical demonstration by an experienced hand, by which the amateur enthusiast can expect to produce a high-grade mirror. Concentration and study are necessary to accumulate knowledge and experience.

Measuring the Paraboloid.

If the preceding facts have been clearly understood, the actual measurement of the paraboloid should be easy to understand It consists simply in measuring the difference of radius between the centre and the edge of the mirror, or between the centre and any selected zone. In order to see the centre distinctly, separate from the edge, it is necessary to cover up all the surface of the mirror, leaving only two

narrow strips on the centre and two on the edge Fig 15 shows the method of marking and cutting out a suitable card. The card should be of the same diameter as the mirror with a projection left at the bottom, so that it may be cut and adjusted to a suitable height to cover the mirror exactly. The knife edge and mirror had better be set up and adjusted prior to placing the card in position. When the card is placed

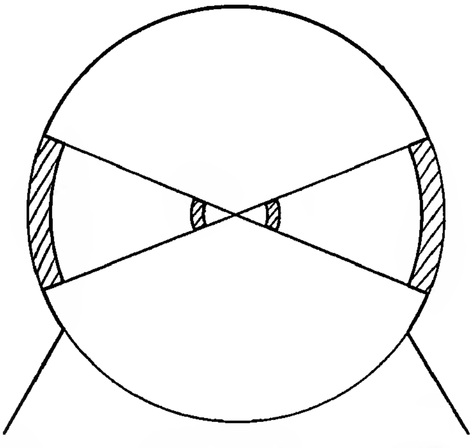


Fig 15 —The card used for covering the mirror during zonal testing

over the mirror and the knife edge moved across, the moving shadows of the two zones left uncovered will be surprisingly clear By moving the knife edge out and in, the shadows can be distinctly seen travelling across, according as the knife edge is within or without the centre of curvature of the particular zone, the shadows of the outer zone will travel in the opposite direction to those of the inner zone In order to find the exact difference of radius between any zone and the centre of a paraboloid, use is made of the mathematical formula $\frac{r^2}{R}$, where r is the radius in inches of the zone under

test, and R is the radius of curvature of the mirror in inches. Take for example the 6-in mirror mentioned in previous chapters. Here, for the edge, r is equal to 3 in, and R is equal to 96 in., or double the focus.

$$\frac{r^2}{R} = \frac{3 \times 3}{96} = \frac{9}{96} = \frac{3}{32} \text{ in. or } \cdot 09375 \text{ in.}$$

Correction.

This amount is theoretically right for a mirror of this size and focus, but in practice it will be found to be slightly in excess. As has been pointed out elsewhere, a sudden slight rise or fall in the temperature will cause the mirror to change its figure, a fall making the curve deeper or in the direction of a hyperboloid and a rise making the curve shallower or tending towards a sphere During practical observation the atmosphere is steadily undergoing change, the temperature steadily falling after the sun sets and in the morning steadily rising as the sun rises Generally, most observing is done in the evening, after sunset, when temperature is falling and it is usual to correct mirrors for these conditions, i e. to slightly under-correct

Occasionally a mirror is made specially over-corrected for observing planets in the morning, when the temperature is on the rise, but in general a slight under-correction is the most useful.

The amount of under-correction allowed in practice is very small In the case of the 6 in, instead of $\frac{3}{32}$ in. or ·09375 in about $\frac{1}{12}$ in. or ·083 in. would give quite a good under-correction for ordinary working conditions in our British climate, or approximately 10 to 12 per cent less. In climates where temperature falls very sharply after sunset, as in semi-tropical countries, under-corrections as high as 50 to 70 per cent less may have to be allowed for For early morning work the same percentage allowances may be taken as a general guide for over-correction. It must be realized

that this allowance for rise or fall in temperature does not mean a fully corrected mirror which stays fixed The correction of a plate-glass mirror may change continually on certain nights as the temperature of the air changes with intermittent breezes set up by passing clouds.

Pyrex will show exactly similar changes, but to a much less degree, though it would settle to its final figure very much more quickly, and this must be borne in mind when making allowance for under-correction In districts where temperature conditions are reasonably steady, a very small under-correction only need be allowed, round about 3 to 4 per cent. In fact a fully corrected pyrex mirror will perform well enough under ordinary conditions to satisfy the ordinary observer If the amateur mirror maker can produce a parabolic curve in pyrex so accurate that temperature changes, during observing, interfere with definition, he is an artist, and should be quite capable of making the necessary correction unaided.

Practical Application.

The card system has the advantage of being fairly simple in use, but it still needs a critical eye with shadow testing experience behind it to distinguish when the shadows on either side are in balance. When the card is placed centrally over the mirror, and the knife edge brought into action at the centre of curvature, the central shadows will show a slightly different radius from the outside zones, differing by the amount given by the formula $\frac{r^2}{R}$. First take the outside zones and note when a balance is arrived at, both zones darkening down evenly Very delicate movement of the knife edge is essential, both in cutting across the beam of light and in the exact distance from the mirror. If the knife edge is within or without this exact point, even by a small amount, the shadows on either side will not balance or cancel out evenly, but will behave in a manner consistent with the

position of the knife edge. Perhaps the easiest way is to treat the zone as a sphere and adjust the knife edge accordingly, i e until both sides darken down equally at the same time

When this position is reached, a line is drawn with a pencil along one of the straight sides of the base of the knife edge. This is the exact centre of curvature of the outer zone. A piece of drawing paper or thin cardboard should have been previously fixed with drawing-pins below the knife edge for this purpose

The centre zone is treated in exactly the same way, only more difficulty will be experienced in deciding when the two sectors are darkening evenly. One way is to move the knife edge a few times rapidly across and note the general movement of the shadow, its travel being decidedly more distinguishable under rapid movement

Another way is to cut a round hole in the centre of the card about 1½ in diameter instead of the two small sectors By treating this central disc as a sphere and adjusting until no travelling shadows are distinguishable, another line may be drawn along the edge of the base Now this line must be nearer the mirror than the previous one if the figure is a paraboloid, as the radius of the centre must be shorter than that of the edges The separation of the lines may now be measured either with a fine scale rule and magnifier, or by means of dividers, and compared with the amount calculated. If the difference is too little, the curve has not been deepened enough, and if too great, parabolizing has been overdone. Careful check should be kept that the curve is being maintained in a regular even sweep with no harsh shadows showing, as they will indicate zones and should be carefully studied and remedied A series of measurements should be made and the average taken, both with the open hole and sector centres. Provided the open shadow test shows a regular flowing curve, the mirror may now be considered to be properly parabolized.

Large mirrors are parabolized and checked for zones just

in the same laborious way The test known as the *Hartman test* is used chiefly in checking up on professionally made mirrors. A special cover is placed over the mirror with a series of holes across the diameter, with small sliding shutters so arranged that any particular zone may be uncovered at will. The lamp and knife edge are adjusted for the particular zone under test, and the results checked photographically.

CHAPTER X

Silvering

Merits of Different Processes.

The parabolic mirror being made, it now remains to silver it, so that it may be ready for mounting, and testing directly on a star. As has been pointed out in Chapter II, the film of silver is chemically deposited on the curved surface of the mirror, and is so very thin and even that it does not materially interfere with the fine accuracy of the mirror.

The process of silvering is often regarded by the amateur as an expert's job. It is purely a straightforward chemical process, which requires just that little bit extra care in selecting pure materials and observing perfect cleanliness. Perfect cleanliness is the key to success Any person with an elementary knowledge of chemistry should find no difficulty in successfully silvering a mirror of medium size.

Many processes are in general use, some of them trade secrets, but the majority depend on sugar as the basis of the reducing agent Brashear's process, although not so simple to manipulate as some, holds its own from a purely reflective point of view, and, if the instructions given are closely followed, should present no difficulty. A simpler

process and one less liable to failure makes use of Rochelle salts This method is very handy for temporary silvering for preliminary testing, though its reflective powers are not so good as Brashear's Nevertheless, it is extensively used by a large number of amateurs, who would have nothing else

For those who would like to try the experiment of comparing the reflective powers of silvered surfaces, it may be stated that the method adopted depends on the loss of light by repeated reflection from a number of surfaces From 15 to 20 flat silvered surfaces are set up, so that a parallel beam of light from a lamp and condenser is reflected from one to the other in a zigzag fashion, and the strength of light from the last one is measured The loss of light from one surface only would be difficult to measure accurately without special equipment, but from 15 surfaces the loss is sufficient to afford an easy comparison

Cleaning the Mirror.

Before silvering can be attempted, the glass surface must be made chemically clean Those with chemical experience will fully understand the meaning of this, but to the majority the process will be better understood if described in detail. The mirror, as it leaves the tool, even if well washed, is far from being chemically clean After a thorough washing with soap and water, making sure that there is no grit present to cause scratches, a little strong pure nitric acid is poured on and thoroughly rubbed over the entire surface of the mirror with a piece of clean cotton-wool. When certain that every part of the surface has been covered, rinse off the acid with plain water and apply a second dose, repeating the operation Again, after a thorough rinse with plain water, flush with distilled water and then put into a dish of distilled water until ready for silvering. If the surface is chemically clean there should be a film of water adhering evenly all over it, even when drained, but if dry patches appear here and there suddenly, these are still greasy and the process

must be done over again. On no account must the surfaee be allowed to dιy off after cleaning, but it must be kept clean by immersion in distilled water until ready for silvering Nitric aeid is exceedingly eorιosive and care is necessary to prevent a bad burn to the fingers Use a large enough pieee of cotton-wool to ensure that the fingers are kept well elear and do not spare the water should any spots get on the hands If, by aeeident, some is spilled on the skin, wash off immediately with plenty of water, applying weak ammonia or soda if neeessary, to neutralize the acid, and then apply a soothing ointment Bad burns should be treated by a doetor

Brashear's Process.

The writer has found the adaptation given below of the usual Brashear formula very eonvenient as a labour saver, in that it does away with the troublesome job of ealculating and weighing out small quantities each time silvering has to be done

Perhaps the greatest objection to Brashear's process in the eyes of the trade is the necessity of keeping the temperature of the solutions below 64° F (18° C) and the fact that mixed solutions cannot be kept without danger A word of caution will not be out of plaee here to those not familiar with this process At temperatures higher than 64° F there is the danger of the formation of small quantities of fulminate of silver, a substance whieh is highly explosive For the same reason, a solution of ammoniated silver nitrate should never be kept or allowed to dry up A few cases of minor explosion have been recorded, but in every case the eause has been traeed to carelessness in working at too high temperatures or keeping an ammoniated solution of silver nitrate.

The quantity of silver nitrate required to give a good eoat suitable for an astronomical mirror may be found by the following rule

$$\frac{\text{square centimetres}}{27} \text{ or } \frac{\text{square inehes}}{4}$$

$$= \text{Number of grammes of silver nitrate required.}$$

Reducing Solution.

The following reducing solution should be made up a few days in advance, as the longer it is kept the better it works The quantity given is enough for a large number of mirrors, and it should be bottled and kept as a stock solution. If put into a stoppered bottle, it will keep for years if necessary. If any difficulty is found in making up this reducing solution, the local chemist could be entrusted with the job, as it is comparatively inexpensive. Reducing solution:

Pure sugar	90 gm.
Nitric acid	4 c.c.
Alcohol	175 c.c.
Distilled water	1000 c.c.

Pure crystal sugar should be used (i e the large crystal sugar, not granulated or loaf sugar, as these contain traces of the chemicals used for whitening) The sugar, nitric acid and water should be placed in a glass vessel and boiled for a few minutes Failing a glass container, a new unchipped enamelled pan may be used After the mixture has cooled, the alcohol is added and thoroughly mixed and then bottled for use.

Silvering Solution.

The following stock solutions should be made up and bottled A dark bottle should be used for the nitrate solution as silver salts are affected by light A waxed cork should be used in the bottle containing the caustic solution, as trouble may be experienced with a glass-stoppered bottle.

A.	Silver nitrate	20 gm.
	Distilled water	to 200 c.c.
B.	Caustic potash	10 gm.
	Distilled water	to 100 c.c.
C.	Silver nitrate	2 gm.
	Distilled water	to 20 c.c.

Solution C may be made with A and measured out afterwards as required If the distilled water is pure enough, these solutions will keep a long time *The nitrate solution can only be kept if no ammonia has been added and any ammoniated solution must be poured out if not used* (see p 68)

The above quantities are sufficient for a 10-in mirror. For the 6-in , previously discussed, the amount of nitrate required will therefore be (taking the area as πr^2 or 28 sq in.)

$$\frac{28 \text{ sq in}}{4} = 7 \text{ gm. silver nitrate}$$

In solution A there are 10 c c of solution to every gramme of nitrate, or in this case $7 \times 10 = 70$ c c In B there is half this weight of caustic potash, or $3\frac{1}{2}$ gm , and as every 10 c c. of solution contains 1 gm of caustic, the volume will be $3\frac{1}{2} \times 10 = 35$ c.c

Solution C is only a reserve solution (which may be taken from the stock bottle) and will be about 7 c.c. To put these quantities in clearer form:

For a 6-in. mirror.

A.	Silver nitrate Distilled water	Stock solution 70 c c (7 gm silver nitrate)
B.	Caustic potash Distilled water	Stock solution 35 c c ($3\frac{1}{2}$ gm caustic potash).
C.	Silver nitrate Distilled water	Stock solution 7 c c ($\frac{2}{3}$ gm. silver nitrate)

Now comes the most difficult part of the process, viz. adding the requisite amount of ammonia to solution A. The ammonia should be full strength, ·880, and pure Add the ammonia slowly, preferably from a dropping bottle. The solution will immediately turn a dark brown colour and will remain so until sufficient ammonia has been added, when the solution will suddenly become clear *It should be added drop by drop, stirring all the time*, until the solution appears a straw colour,

when a dilute solution of ammonia and distilled water may be used to finish the process The solution should be almost clear, with a trace of milkiness left If it is absolutely clear it shows an excess of ammonia A few drops of the nitrate solution may be added to regain the trace of milkiness or dimness

Solution B may now be added, when the mixture will turn a dark brown or black Again add ammonia, drop by drop, stirring constantly until the solution just clears up to a light brown or straw colour, but transparent Now add a proportion of solution C, when the liquid will turn dark again. This is to ensure that the silver is in excess, a condition necessary to the success of the process When the solution has a decidedly muddy appearance, which no amount of stirring will dispel, it should be filtered through absorbent cotton-wool, when it is ready for use No more than the quantity needed for the mirror should be ammoniated at one time

For every gramme of silver nitrate in the silvering solution 6 c.c of reducing solution should be measured out and kept in a separate dish For the 6-in mirror, therefore, $7 \times 6 = 42$ c c. of reducer should be used

As Brashear's process deposits the silver downwards, the *prepared* mirror should be lying in the dish, face up, covered with distilled water This water need not be poured off, but the silvering solution and reducer poured on, when the silver will start depositing immediately The process will be complete in from 3 to 8 minutes, according to the temperature, which should not be more than 64° F. or 18° C. Keep the solution in motion during silvering to prevent the sediment from settling on the silver film. The dish may be tilted to one side to observe progress, but the film should not be exposed to the air for more than a few seconds at a time.

If a suitable glass dish is not obtainable a waxed paper strip may be wound round the edge of the mirror in such

a manner that it forms a wall about 2 in high If this is tightly wound and firmly tied with string or tape, a very convenient dish is formed by the mirror itself.

Great care must be taken to keep the face of the *prepared* mirror covered with a film of distilled water during this procedure, and on no account must it come in contact with the hands, or bare patches will be left after silvering The cleaning with nitric acid may be done after the band has been fixed, but there is great danger of traces of the acid being left in the crevice between the wax band and the mirror A few drops of ammonia in the first rinsing water will help to neutralize this, but thorough rinsing is essential if the latter method is adopted

On the completion of the process the spent solution should be poured off quickly and the mirror rinsed with plain tap water, and finally swilled with distilled water, after which it should be set up on edge to dry If there is much scum on the surface when it is being rinsed with tap water, a light swab with cotton-wool will help to remove most of it and save work on the final polishing It must be remembered that the film when wet is very delicate and easily damaged and should be swabbed very lightly. When dry—it should be dried in a warm atmosphere—the mirror is ready for final polishing.

Rochelle Salt Formula.

This process is very much simpler, but the same care has to be exercised in regard to accuracy and cleanliness. Approximately the same quantities of silver salt may be used to give a sound film, i e. 7 gm for a 6-in. mirror. Stock solutions may be made up as follows:

A.	Silver nitrate	30 gm.
	Distilled water	to 300 c.c.
B.	Rochelle salt	4 gm.
	(Sodium potassium tartrate)	
	Distilled water	to 40 c.c.

B is a 10 per cent solution, and should be boiled for at least 20 minutes in a glass container before being bottled, any water lost by evaporation being made up

After the mirror has been made chemically clean, and just before silvering, a strong solution of stannous chloride should be freshly made and flowed all over the surface Afterwards thoroughly rinse with tap water, with a final flush of distilled water, then immerse the mirror directly into the silvering solution The silvering solution consists of:

Solution A . ..	8 parts.
Solution B ..	1 part.
Water . ..	64 parts.

In quantities suitable for a 6-in mirror.

Solution A . ..	72 c.c.
(which contains fully 7 gm. silver nitrate)	
Solution B	9 c.c.
Distilled water	596 c.c. or 600 c.c.

The 72 c c of silver nitrate solution should be ammoniated by adding ammonia (.880) until the liquid clears, as explained in the description of the first part of Brashear's process, just leaving a trace of milkiness.

Solutions A and B are now poured into the container and the mirror, previously treated with stannous chloride, immersed in the liquid face down, not face up as in Brashear's method. The surface of the mirror should be just under the surface of the liquid, about $\frac{1}{8}$ in. The mirror should be placed into the solution one edge first, and gently tilted level to dispel the air bubbles, which will be trapped by the concave surface. The time taken to deposit a good film of silver by this process may be anything from a few minutes to an hour, or more, according to the temperature and the accuracy with which the solutions have been prepared. As this process is rather flexible, a trial should be made (and the time noted), with a

small quantity of the solution in a glass dish, cleaned and prepared in the same way as the mirror Another way, applicable to both processes, is to insert small strips of prepared glass (such as pieces cut from lantern slide cover glasses) into the liquid and examine from time to time to see the progress of the silvering. In both processes a little extra water does no harm and the quantity may be varied to suit the size of dish being used About ¾ in of solution should be allowed above the face of the mirror in Brashear's method, and about the same amount under the mirror in the Rochelle salt process

A method largely used is to silver by the instalment plan, which, although a little more expensive in chemicals, has the advantage of giving a brilliant film, free from pinholes By giving the mirror two or three applications of half or three-quarters strength, making up the bulk with water, the silvering at each application may be stopped short just when the film is most brilliant and before the scum or "bloom" begins to form through prolonged immersion The total amount of silvering solution may be prepared at one time and divided into two or three parts as the case may be, and the required amount of reducing solution measured and kept in separate glasses The solutions must be kept separate until the moment they are poured into the silvering dish, as silvering begins immediately they are mixed

A good guide as to the proper thickness of film is to look through it at the filament of a gas-filled lamp The film will look a bluish colour and the filament should just be distinguishable at 3 feet and should be free from pinholes.

Polishing and Care of Film.

The silver coating, after it has thoroughly dried, will have a greyish scum over the surface, and this requires to be polished off Polishing a silver film is undesirable at any time, through the risk of damaging the highly polished surface, hence the great advantage of the instalment plan, which if

properly carried out requires a minimum of polishing. Two pads of the finest chamois skin should be made up, about 2 in diameter, with cotton-wool in the centre The chamois skin should be free from dust and grit of any description, or scratching will be sure to result To polish, one pad is used very lightly and gently in circular strokes, as in French polishing, to remove the loose grey powder adhering to the surface A gentle touch is needed, as this grey matter is very liable to scratch The second pad is dipped in rouge and rubbed on a piece of perfectly clean glass to distribute the rouge, and used in exactly the same way as the first pad, but more freedom can be used as the rouge is not so liable to scratch Stray dust or grit must be guarded against, as this is the greatest enemy to successful polishing. The first pad may be unnecessary if the Rochelle salt process has been used, as it generally leaves the surface free from a grey deposit

Once a film has been polished and finished it should not be touched again, as subsequent polishing will only result in spoiling the film To keep a silvered mirror for any length of time in an untarnished condition, it must be enclosed in a cell with a close-fitting cover Moisture from the atmosphere tarnishes silver very quickly, and an unprotected film will tarnish in a matter of a week or so during damp weather. To preserve a mirror in good condition, a pad made up of good quality blotting-paper, stitched together and fitted inside the cell cover, is very useful, as it absorbs moisture trapped in the air, when the cover is replaced after use. The pad may be occasionally baked in an oven to thoroughly dry it out and make it more absorbent. Under such conditions a silver film will keep bright for a year at least, in ordinary country air. In towns or near factory chimneys, the sulphur fumes present may shorten its life.

Pure distilled water is recommended for all solutions containing silver nitrate For some people it may be difficult to obtain. Clean rain-water, if caught in glass vessels from a clean slate roof, after three or four hours' steady rain, will

answer quite well. To test the water, put some in a small test tube and drop one or two tiny crystals of silver nitrate into it If it remains perfectly clear the water is good, but if it turns milky or cloudy, the water contains impurities and should not be used

In Glasgow the ordinary domestic water supply is so pure that it can be used direct from the tap and works excellently. The Glasgow water is exceptional, of course, but other supplies may be found equally good. The writer uses nothing else, bringing his supplies from Glasgow, as the local supply is unsuitable

A word on the purity of the chemicals used for silvering. Only the purest chemicals should be used if disappointment is to be avoided. A reliable source should be found and adhered to, preferably direct through some wholesale concern or laboratory suppliers One impure commodity will upset the whole process, just as impure water will do

CHAPTER XI

Star Testing

Appearance of a Star.

Testing a telescope, whether it be a reflector or a refractor, by means of a star, requires a certain amount of experience in order to train the eye to see the appropriate detail, just as was necessary with the knife-edge test. The condition of the atmosphere will be another factor which has to be contended with in our British climate. A first-rate telescope on a " poor seeing " night may show up worse by comparison than a poor telescope on a good night owing to the unstable conditions in the intervening air. Testing under these con-

ditions, therefore, will depend largely on the experience of the user for reliable results Only by patient effort under all atmospheric conditions can sufficient experience be gained to enable the user to distinguish between a good and a bad telescope With a first-grade mirror, properly centred and adjusted, the image of a bright star should appear as a small round central dot of light surrounded by one or two faint narrow rings known as diffraction rings Those rings are not part of the star itself but an optical phenomenon, due to diffraction, or interference between the light waves as they travel from the mirror to the eyepiece The inexperienced will have difficulty at first in seeing any trace of diffraction rings, but once the eye has become familiar with their appearance their impression will always remain A bright star, such as one of first or second magnitude, will show the rings more readily than one of fainter magnitude A fainter star may fail to show any trace of a diffraction ring at all, the ring being too faint to be detected by the eye, though present.

These rings can be utilized to reveal defects in parabolizing which even the knife edge may fail to show clearly. If the star image be examined with a fairly high power eyepiece, e g a power of 200 for a 6-in mirror, a fair idea of the general perfection of the curve may be formed If the general figure is good the central spot of light should still remain small and sharply defined with one or two faint rings concentrically surrounding it Most probably, if the mirror is a first attempt, no trace of diffraction rings will be seen at all, but the image of the star will appear as a diffused disc of light of appreciable size, more like a tiny woolly ball of light with no definite sharp outline.

Out of Focus Images or Diffraction Rings.

The worker need not be discouraged, however, as he is now in the position to see exactly where the errors lie in the curve. If the eyepiece is racked about a quarter of an inch inside the point of focus, the size of the image will increase, and it

will break up into a series of rings of varying thickness and brightness A further examination should now be made with the eyepiece the same distance outside focus For accuracy a line should be drawn with a pencil on the focussing jacket at focus and the appropriate distance marked on either side.

Now, if the mirror is a perfect paraboloid, the rings should be of equal thickness and brightness from the centre to the edge, and both inside and outside focus their appearance should be the same, both as regards brightness and number If the curve departs from the parabolic, the system of rings will show marked differences in thickness and brightness at various points from the centre to the edge, according to the variations of the curve from a paraboloid, those inside focus being the reverse of those outside The thick bright rings inside focus will be the thin weak rings outside These rings are still not too easy to see to an "uneducated" eye, but after a little practice they should be seen easily If the mirror is very far out or very poor, only one thick ring may be seen on one side and a large spot in the centre on the other side of focus

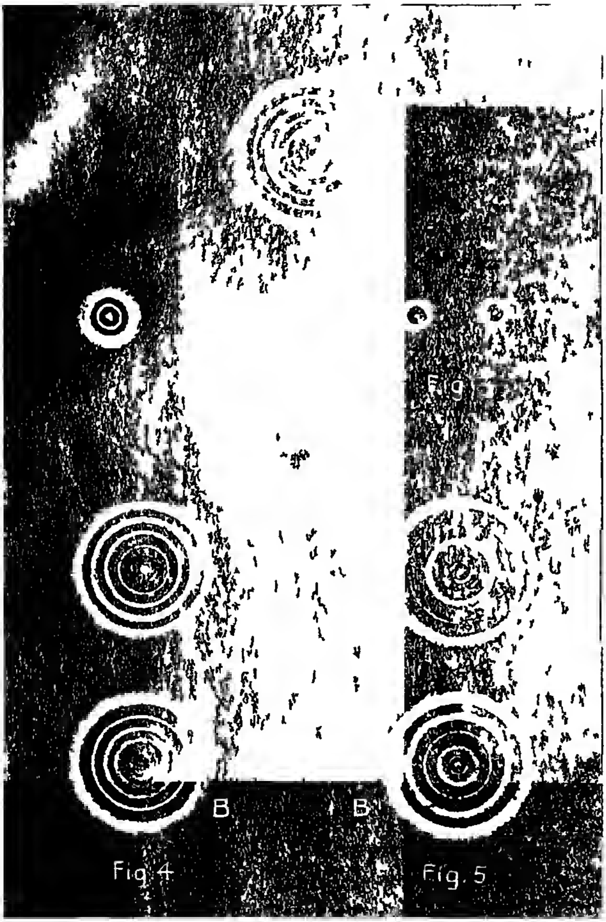
In Plate IV an attempt has been made to reproduce the writer's impression of "out of focus" or "extra focal" images Only on extra good seeing nights with a steady atmosphere can the reader expect to see such sharp and clear images as the drawings portray

Fig 1 is the appearance of an extra focal star image, highly magnified, about $\frac{1}{4}$ in from focus, such as would be shown by a perfect telescope A reflector with a relatively large flat would show the centre rings slightly dimmer than the illustrations The appearance should be the same at equal distances inside and outside focus

Fig 2—The same image inside and outside focus but much nearer the focal point.

Fig 3 is the appearance as seen very close to focus.

Fig 4—The out of focus images by a mirror showing two slight zones A zone near the outer edge shows too



Out of focus star images

short a focus, while the centre zone is of too long a focus. A is within, and B is beyond focus

Fig 5—An example of bad zones in a mirror This indicates an irregularly flowing curve Only the centre and outside zones are of the same focus, the intermediate rings showing zones of long, short and long focus respectively. A is within and B is beyond focus

In order to fully understand the significance of diffraction rings, it is necessary to know exactly what they represent. When examined under high power, the reflected rays of light from a parabolic mirror, owing to mutual interference, resolve themselves into a series of concentric rings of equal intensity at equal focus, the nearer the exact point of focus the fewer and brighter the rings The reader may verify this remark from figs. 1, 2 and 3, Plate IV If the curve of the mirror is not a true paraboloid but contains zones of slightly different focus, it follows that these zones will be represented by rings of different intensity according to the proximity of the eyepiece to their point of focus Again, if every zone of the curve is of the same focus, all the diffraction rings will be of equal thickness and brightness, but any zone not of the same focus will be represented by weak thin rings or otherwise will appear less intense The brighter the ring the thicker it also appears Therefore it will be seen that an out of focus image (i e diffraction rings) presents directly to the eye a miniature picture of the state of the curve, showing long or short focus zones in their relative positions Short focus zones will show as bright thick rings, when the eyepiece is within focus and as thin weak rings when without focus. Longer focus zones will appear brighter without focus than when examined within focus.

In order to make reliable comparisons, the distance within and without focus must be the same. Tests at different out of focus points should be made as well as tests on different nights. They will then form a reliable guide as to the state of correction of the mirror.

Artificial Star.

An artificial star may be used to carry out the above tests, but it must be placed at as great a distance as possible, in order that the rays of light may be as nearly parallel as possible The pinhole lamp may be used for this with a very small pinhole, e g $\frac{1}{100}$ in , placed approximately 100 feet distant With an oil-burning lamp this size of hole may prove to be rather dim in comparison with a star, so it is usual to use the filament of an electric lamp placed directly behind the pinhole An artificial star is most useful on "bad seeing" nights, when the condition of the atmosphere prevents one from using the more distant orthodox star

Double Stars.

For the amateur who has perfected his telescope to the best of his ability, double stars afford quite a reliable means of making a definite comparison with a first-class instrument Here again the eye requires " education " to distinguish and separate close double stars

Theoretically there is a certain limit to the resolving power or separating ability of a given size of telescope. It takes a telescope of really first-class quality on a good night to separate double stars down to this limit A list of double stars suitable as test objects for telescopes of various apertures may be found in most good handbooks of astronomy. The Handbook of the British Astronomical Association for 1922 gives a list of test doubles for telescopes from 1 in. to 10 in. aperture, which affords a high standard of test for an amateur instrument Suffice it to say that a separation of 8 second of arc is a severe test for a 6-in reflector on a good night Castor with a separation 3 93 * seconds of arc is a good test to start off with Though theoretically within the range of a 1-in. telescope, its brightness makes it rather difficult for a 6-in. unless it be of fair quality If Castor can be separated com-

* B A A Handbook 1937.

fortably, closer and more difficult doubles should be tried until the limit is found, which will give a good indication of the quality of the instrument

The quality of the mirror will limit the magnification or power which can be used Beginners are warned against using unnecessarily high powers, as more of the beauties of the sky will be seen with low and medium powers, but it is gratifying to know that one's telescope is capable of a good performance with high power just when it is needed, i e. on a good night, on the moon or planets

A telescope of medium quality will give a fair account of itself on the moon, showing all the craters and mountain ranges, but to be of real service to a serious observer it should be capable of defining fine detail, such as the intricate systems of small hills and clefts of the various craters. To do this, good definition and high power are needed, ideals which are not beyond the capabilities of an ordinary amateur with a little patience and perseverance

CHAPTER XII

Notes on the Mounting of Small Reflectors

The construction and mounting of an astronomical telescope are outwith the scope of this book, but a few notes on the subject may serve as a guide

The Flat or Diagonal.

The small plane mirror set at 45°, known as the *flat* or *diagonal*, requires to be of the same optical perfection as the mirror itself. Ordinary sheet-glass is far from being perfectly flat, the system employed in polishing on a commercial scale

leaving the surface wavy and irregular. However, some brands of heavy plate-glass about $\frac{5}{8}$ in or $\frac{3}{4}$ in thick are reasonably flat, and from half a dozen pieces one or two may be found to be near enough to serve the purpose The writer has found an occasional discarded motor windscreen of the plain glass type (not triplex) of excellent flatness, although the majority are useless for the present purpose

A really good mirror requires a good flat to avoid spoiling its perfection, and it is recommended in this case that a flat should be purchased from some reliable maker of repute, but with the average amateur-made mirror a good plate-glass flat will perform excellently The cutting out and mounting of such a flat is well within the capabilities of an ordinary amateur with a lathe at his disposal

American amateurs prefer a right-angled prism to a silvered flat Though a prism will reflect more light than a flat, in practice this advantage is partly offset by the shape of the prism, which presents a greater obstruction to the light passing down the tube A prism has the advantage that it has no silvered surfaces to tarnish, but against this, it must be of really first-rate quality to avoid spoiling the definition of a good mirror, and it also is much more expensive than a good silvered flat

The mirror cell and the mounting for the flat must be so arranged that they can be easily adjusted relatively to the optical axis of the telescope A badly adjusted reflecting telescope will never perform well, no matter how good the mirror and flat

The Tube.

Controversy still continues over the question of the tube for an astronomical reflector—whether it should be of an open skeleton or solid enclosed type.

From practical experience, the writer advises the solid wooden tube The open girder-work tube may be an advantage over a solid metal tube in large sizes, where the enormous

weight of the mirror prohibits the use of wood from a structural point of view, but in the small sizes the wooden tube has the advantage In a metal tube the conductivity of the metal sets up internal eddy currents of air inside the tube, due to difference of temperature between the highest and lowest points In large sizes this becomes serious, hence the advantage of the open skeleton type of support, but in small sizes the open type of support is open to the objection that the heat radiated from the hands and body of the observer, as well as from the breath, set up more eddy currents than a close wooden tube possibly can Wood, being a non-conductor of heat, maintains a steadier temperature inside the tube than metal, and gives greater stability. It is granted that the adjustments with a metal tube may be more permanent, but a wooden tube need give no trouble if well designed and handled properly

Thin plywood, bent by steaming, of the required number of sheets to make up a tube $\frac{1}{2}$ in to $\frac{3}{4}$ in thick makes an excellent light and rigid job if reinforced at the ends with metal bands A square wooden tube is not to be despised and has the advantage of easy construction and simplifies the fitting of the focussing jacket A thickness of 1 in at least is advised for a 6-in telescope

The Mounting.

A reflecting telescope of 6 in aperture and upwards is an unwieldy instrument to use without some form of mounting For the smaller sizes below 4 in an altazimuth mounting may serve the purpose, but for serious work some form of equatorial mounting is essential Whatever type is chosen it must be rigid, with a smooth steady motion A telescope that shakes or vibrates is useless for astronomical work of any kind. The German type of mounting can be made up easily and cheaply from a variety of discarded engineering parts, and some very ingenious and satisfactory mountings are in use by well-known amateurs throughout the world.

Eyepieces.

The subject of eyepieces might well occupy a complete book by itself For a reflector of ordinary quality nothing can beat the Huygenian eyepiece if it is of good quality. So many eyepieces of poor quality are on the market, that the amateur is advised to deal only with reputable firms, either for new or second-hand eyepieces Old microscope eyepieces may sometimes be picked up which give good results, but the advice is to buy as good an eyepiece as can be afforded One good eyepiece is worth more than half a dozen poor ones.

With a fairly good mirror a critical observer will soon find that the Huygenian form of eyepiece suffers from one defect, i e want of flatness of field When an object is focussed in the centre of the field of view it will be found to lose in definition as it travels towards the edge, rather a disadvantage when observing objects covering the greater part of the field of view

The achromatic eyepiece overcomes this defect, having a practically uniform flat field This type is more expensive than the former type and even second-hand commands a good price—from 21*s* to 30*s*., according to focus. The purchase of one good achromatic of high power is well worth while, and, if it can be afforded, a complete range

The question of magnification or power of an eyepiece is often a source of difficulty to a beginner Eyepieces are listed as being of a certain equivalent focus, e g 1 in. E F To arrive at the power or magnification of an eyepiece with a given telescope, the focus of the telescope is divided by the equivalent focus of the eyepiece With a telescope of 48 in focus and an eyepiece of $\frac{1}{4}$ in E.F therefore the power is

$$48 - \tfrac{1}{4} = \frac{48 \times 4}{1} = 192.$$

Further, to find the focus of an eyepiece for a given power,

the focus of the mirror is divided by the power. Thus for a power of 192 the focus of the eyepiece would be

$$48 - 192 = \frac{48}{192} = \tfrac{1}{4} \text{ in}$$

The above method is quite suitable if the equivalent focus of the eyepiece can be relied on to be accurately marked, but unfortunately the makers of the more common types are very haphazard in their methods of marking The power of any eyepiece can be accurately measured, however, by means of the *Ramsden disc*, a method discovered by the celebrated optician Ramsden When an eyepiece is placed in the telescope and focussed on a brightly illuminated distant object or on the clear sky, an image of the mirror is formed in front of the eyepiece If the eye is placed about 1 foot behind the eyepiece this image will be seen as a small, sharp, round, bright disc, with the shadow of the flat as a small dot in the centre This is the Ramsden disc Since it is a real image, its diameter can be accurately measured by means of a caliper gauge or a decimal wire or sheet metal gauge The latter is a gauge having a long tapered slot, with its edges graduated in thousandths, and affords a very accurate means of measuring the disc To calculate the power of the eyepiece the clear diameter of the mirror is divided by the diameter of the Ramsden disc For example, if the diameter of the disc is $\frac{1}{8}$ in and the aperture of the telescope 6 in ,

$$6 - \tfrac{1}{8} = \frac{6 \times 8}{1} = 48$$

is the power of the eyepiece with that particular telescope. Again, if with the same telescope the Ramsden disc measures $\frac{1}{20}$ in or ·05 in , the power will be

$$6 - \tfrac{1}{20} = \frac{6 \times 20}{1} = 120.$$

If the focus of the above telescope is 48 in., then the equivalent focus of this eyepiece will be

$$48 \div 120 = \tfrac{48}{120} = \tfrac{2}{5} = \cdot 4 \text{ in.}$$

The question of the number of eyepieces is generally decided by the size of the purse of the owner. A 1-in. eyepiece is a good proposition for a beginning, followed by a $\frac{1}{2}$-in. Then a good low power of $1\frac{1}{2}$ in. may be obtained, followed by higher powers, if the amateur finds that the definition of his mirror will stand it. For higher powers good achromatics should be selected such as Browning's Achromatic, a Zeiss Orthoscopic, or similar type. A power of 250 or 300 is about the useful limit for a 6-in. mirror, unless it is of exceptionally good quality. Larger apertures will stand proportionately higher powers with their greater light gathering power, a factor which limits the distance to which magnification can be pushed.

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